WL-TR-97-3076

HALON REPLACEMENT PROGRAM FOR AVIATION, AIRCRAFT ENGINE NACELLE APPLICATION PHASE II – OPERATIONAL COMPARISON OF SELECTED EXTINGUISHANTS

Mr J. Michael Bennett
Capt Gregg M. Caggianelli

Survivability and Safety Branch
Vehicle Subsystems Division
Air Force Research Laboratory
Wright-Patterson AFB OH 45433-7605

Mr Mathias L. Kolleck
Mr Jon A. Wheeler

Booz•Allen and Hamilton Inc
4141 Colonel Glenn Highway
Suite 131
Dayton, OH 45431-1662

MAY 1997

FINAL REPORT FOR PERIOD OCTOBER 1993 – SEPTEMBER 1994

FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7562

NOTICE

USING GOVERNMENT DRAWINGS, SPECIFICATIONS, OR OTHER DATA INCLUDED IN THIS DOCUMENT FOR ANY PURPOSE OTHER THAN GOVERNMENT PROCUREMENT DOES NOT IN ANY WAY OBLIGATE THE US GOVERNMENT. THE FACT THAT THE GOVERNMENT FORMULATED OR SUPPLIED THE DRAWINGS, SPECIFICATIONS, OR OTHER DATA DOES NOT LICENSE THE HOLDER OR ANY OTHER PERSON OR CORPORATION; OR CONVEY ANY RIGHTS OR PERMISSION TO MANUFACTURE, USE, OR SELL ANY PATENTED INVENTION THAT MAY RELATE TO THEM.

THIS REPORT IS RELEASABLE TO THE NATIONAL TECHNICAL INFORMATION SERVICE (NTIS). AT NTIS, IT WILL BE AVAILABLE TO THE GENERAL PUBLIC, INCLUDING FOREIGN NATIONS.

THIS TECHNICAL REPORT HAS BEEN REVIEWED AND IS APPROVED FOR PUBLICATION.

J. Michael Bennett

J. MICHAEL BENNETT
Technical Advisor
Halon Replacement Program

Anthony S. Lizza

ANTHONY S. LIZZA
Chief
Survivability and Safety Enhancement Branch

Richard E. Colclough, Jr.

RICHARD E. COLCLOUGH, JR.
Chief
Vehicle Systems Division

Do not return copies of this report unless contractual obligations or notice on a specific document requires its return.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 01704-0188

1. AGENCY USE ONLY (Leave blank)

2. REPORT DATE
May, 1997

3. REPORT TYPE AND DATES COVERED
Final - From October 1993 to September 1994

4. TITLE AND SUBTITLE
Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application
Phase II - Operational Comparison of Selected Extinguishants

5. FUNDING NUMBERS
PR: OAFF
TA: HR
WU: 00

6. AUTHOR(S)
Mr. J. Michael Bennett
Capt. Gregg Caggianelli
Mr. Mathias L. Kolleck
Mr. Jon A. Wheeler

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Survivability and Safety Branch
Vehicle Subsystems Division
Air Force Research Laboratory
WPAFB OH 45433-7605

Booz•Allen and Hamilton Inc
4141 Colonel Glenn Highway
Suite 131
Dayton, OH 45431-1662

8. PERFORMING ORGANIZATION REPORT NUMBER
SURVIAC-TR-96-022

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
FLIGHT DYNAMICS DIRECTORATE
WRIGHT LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE OH 45433-7562
POC: Dennis Weiland, AFRL/VAVS, 937-255-6050
Naval Air/AIR-52031J
1421 Jefferson HWY, Jefferson Plaza II, Rm 970,
Arlington VA 22243-7809

ASC/ENF, WPAFB OH 45433
2335 7th St. Ste 6 , WPAFB OH 45433
Federal Aviation Admin Tech Center
ACD 240 Bldg 277, Atlantic City NJ 08405
US Army Aviation & Troup Cmd/SMSAT-R-EPD
4300 Good fellow Blvd, St Louis MO 63120-1798

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
WL-TR-97-3076

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release: distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report documents the work performed under Phase II - Operational Comparison of Selected Extinguishants - of the Halon Replacement Program for Aviation for the Aircraft Engine Nacelle Application. Phase II is the second of a three-phase program to determine a replacement for Halon 1301 in aircraft engine nacelle applications. The objective of Phase II testing was to determine which of the selected extinguishant candidates, through a head-to-head comparison, was most effective in extinguishing fires in an engine nacelle. Of the 3 extinguishants tested, HFC-227ea, HFC-125, and CF_3I. HFC125 was selected based on its cold temperature distribution capability, and its "Halon 1301-like" flow and discharge behavior.

14. SUBJECT TERMS
Fire Protection; Fire; Halon Replacement; Operational Comparison of Selected Extinguishants; Aircraft Engine Nacelle; HFC125; HFC227ea; CF_3I; Halon1301

15. NUMBER OF PAGES
42

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

TABLE OF CONTENTS

Section **Page**

EXECUTIVE SUMMARY 1

1.0 INTRODUCTION 8

2.0 TEST OBJECTIVE 11

3.0 APPROACH 12
3.1 Phase II Test Series Parameters 12
3.1.1 Varied Parameters 12
3.1.1.1 Fire Location 13
3.1.1.2 Internal Airflow 13
3.1.1.3 Fuel 13
3.1.1.4 Extinguishant Temperature 13
3.1.2 Constant Parameters 13
3.2 Test Matrix 14
3.3 Amount of Extinguishant 16
3.4 Test Article Configuration 17
3.4.1 Aircraft Engine Nacelle Fire Test Simulator 17
3.4.2 Engine Nacelle Configuration 18
3.4.3 Extinguishant Conditioning and Delivery 19
3.4.4 Extinguishants 20
3.4.5 Airflow 20
3.4.6 Data Requirements 21
3.4.7 Data Acquisition and Recording 21
3.4.8 Video 22
3.5 Procedure 22
3.5.1 Qualification Testing 22
3.5.2 Full-Scale Testing 22

4.0 RESULTS 29
4.1 Data Analysis 29
4.1.1 Analysis of the Phase II Factorial Experiment 31
4.1.2 Transformation of the Response Variable 33
4.1.3 Analysis of the Phase II Factorial Experiment After Log Transformation 34
4.2 Phase II Analysis Summary 37

5.0 CONCLUSIONS 39

6.0 REFERENCES 50

LIST OF FIGURES

Figure		Page
1	Adjustable Test Fixture	4
2	Close View of Clutter Around Fire Point	5
3-1	Bracketing Procedure	17
3-2	Adjustable Test Fixture	18
3-3	Close View of Clutter Around Fire Point	19
3-4	Y-Shaped Distribution Tubing	20
3-5	AEN Air Handling System	21
3-6	Picture of Engine Nacelle Fire With Fuel Spray	24
3-7	Diagram of Engine Nacelle Fire With Fuel Spray	24
3-8	Picture of Engine Nacelle Fire With Fuel Spray Turned Off	25
3-9	Diagram of Engine Nacelle Fire With Fuel Spray Turned Off	25
3-10	Picture of Extinguishant Flooding Engine Nacelle	26
3-11	Diagram of Extinguishant Flooding Engine Nacelle	26
3-12	Picture of Engine Nacelle After Fire Extinguishment	27
3-13	Diagram of Engine Nacelle After Fire Extinguishment	27
4-1	Effect Sum of Squares as Percent of Total	32
4-2	Residual Values Versus Predicted Values	34
4-3	Effect Sum of Squares as Percent of Total After Log Transformation	36
4-4	Residual Values Versus Predicted Values After Log Transformation	37

LIST OF TABLES

Table		Page
1	Phase II Varied Parameters and Settings	3
2	Phase II Constant Parameters and Settings	3
3	Phase II Engine Nacelle Test Matrix	6
4	Average Weight of Extinguishants (lbs) - Phase II Test Matrix	7
3-1	Phase II Varied Parameters and Levels	12
3-2	Phase II Constant Parameters and Levels	14
3-3	Phase II Engine Nacelle Test Matrix	15
3-4	Data Collection Worksheet	22
4-1	Phase II Varied Parameters and Levels	29
4-2	Phase II Constant Parameters and Levels	29
4-3	Phase II Engine Nacelle Test Matrix	30
4-4	Analysis of the Phase II Factorial Experiment	31
4-5	Preliminary Analysis of Variance (ANOVA) - Phase II	33
4-6	Analysis of the Phase II Factorial Experiment After Log Transformation	35
4-7	ANOVA After Log Transformation	36
4-8	Average Weight of Extinguishants (lbs) - Phase II	38

PREFACE

This research and development task was sponsored by the Air Force, Army, Navy, and Federal Aviation Administration. Data Management activities for this effort were performed as Task 94-05 under contract DLA900-90-D-0424. This final technical report summarizes work performed under Phase II of the Halon Replacement Program for Aviation, aircraft engine nacelle application, from October 1993 to September 1994. This task was administered under the technical direction of Mr. J. Michael Bennett (WL/FIVS), Wright-Patterson Air Force Base, Ohio.

EXECUTIVE SUMMARY

The Clean Air Act Amendments (CAAA) of 1990 and U.S. Environmental Protection Agency (EPA) rules limit U.S. production of ozone depleting substances (ODS). These actions carry out the United States' obligations under the "Montreal Protocol on Substances that Deplete the Ozone Layer," an international treaty ratified by the Senate in December 1988, limiting global production of such chemicals. Subsequent international and national legislation has dictated the phase-out of the production of these chemicals.

As a result of these actions, the U.S. Air Force made a decision in 1992 to develop a "non-ozone depleting solution" for on-board aircraft fire extinguishing by 1995. This timeline was dictated by the program schedule of the F-22 fighter, so that this alternative solution could be considered for implementation. A program for evaluating and identifying alternative extinguishants that would be commercially available was developed by the Air Force's Wright Laboratory. This program - The Halon Replacement Program for Aviation - was subsequently expanded in scope to include the requirements of all U.S. military and commercial aircraft engine nacelle and military dry bay applications and was jointly sponsored by the U.S. Air Force, Navy, Army, and Federal Aviation Administration. A Department of Defense Halon Alternatives Steering Group was established to oversee this and other similar programs.

A Small Business Innovative Research (SBIR) effort funded by Wright-Patterson Air Force Base investigated a total of 600 chemicals with a configuration similar to the halons as potential replacements. These potential replacement chemicals were investigated for toxicity, physical traits, and fire-fighting effectiveness to determine which had the potential to meet aviation requirements. It was determined that ten chemicals had characteristics acceptable for aircraft use and the capability to generate the necessary supplemental data within the required program timelines. To these ten, the Air Force added two suggested from other data sources. A screening program to reduce this list of 12 to the three best for full-scale testing was conducted by the National Institute of Standards and Technology (NIST). The laboratory-scale testing at NIST was conducted concurrently with Phase I of the full-scale testing at Wright Laboratory.

This report documents the work performed under Phase II - Operational Comparison of Selected Extinguishants - of the Halon Replacement Program for Aviation, Aircraft Engine Nacelle application. This joint program was designed to find a replacement chemical extinguishant for halon as a total-flood fire extinguishant on board military and commercial aircraft. There are two applications considered under this program - dry bays and engine nacelles. This report deals with the engine nacelle application. The concern for engine nacelle fires centers on the space between the engine cowling and the engine core, where fuel lines, hydraulic lines, and other protuberances and equipment are attached to the core. An analogous series of tests was also conducted to determine a halon replacement for the dry bay application. That work was documented in a similar series of reports.

Halons are being replaced because they have been found to deplete the earth's protective stratospheric ozone layer. Stratospheric ozone depletion is predicted to have a significant adverse global impact on human health, climate, and natural environmental systems. Accordingly, international and national legislation has dictated the phase-out of the production of these substances and production has ceased as of 1 January 1994. Halons are important because they have been used as fire extinguishants in military and commercial aircraft since the late 1940s. After many years of operational experience, Halon 1301 (CF_3Br) has emerged as the favored extinguishant for aircraft. This is due primarily to the wide range of applications to which Halon 1301 is suited. However, increasing environmental concerns with ozone depletion have resulted in a mandate to discontinue use of Halon 1301 in new systems, as well as other halons used as fire extinguishants.

There are several important considerations in replacing halon in aircraft fire protection systems. The most obvious among these is the weight and volume of the extinguishant and of the delivery equipment. Since there are severe weight and space limitations on aircraft systems, engineers may be forced to compromise fire suppression capability to comply with a restriction on system weight. This could cause a significant decrease in aircraft and crew member survivability. These were some of the issues considered during this program.

All tests were performed at the Aircraft Engine Nacelle Fire Test Simulator (AENFTS) located at Wright-Patterson Air Force Base (WPAFB), Ohio. The AEN is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine, and to test the effectiveness of the methods used to prevent, detect and extinguish fires in that area. This fixture can simulate a full 360° airflow field and has a realistic helical extinguishant distribution. Figures 1 and 2 show the AENFTS and a closeup of the simulator fire point.

Phase I - Operational Parameters Study - was the first of the three-phase Halon Replacement Program for Aviation. Phase I for the engine nacelle application was completed in August 1993 and is documented in a Wright Laboratory report entitled *Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application - Phase I - Operational Parameters Study*, WL-TR-95-3077, September 1995. The objective of Phase I testing was to determine which parameters (factors) in an aircraft engine nacelle fire most influence the amount of extinguishant needed to extinguish that fire.

Phase II - Operational Comparison of Selected Extinguishants - was the second of the three-phase program. The objective of Phase II testing was to develop full-scale live-fire test data comparing the three candidate replacement extinguishants selected by the Technology Transition (T2) Team in a meeting held at Wright-Patterson Air Force Base (WPAFB), Ohio in October 1993. The selection was based on data generated in Phase I testing at Wright Laboratory and additional testing conducted at NIST. The selected extinguishants were:

- HFC-227ea (Trade Name - FM200)
- HFC-125 (Trade Name - FE25)
- CF_3I (Trade Name - Iodoguard or Triodide)

The data generated under this test program were presented to a Technology Transition (T2) Team to aid in the ultimate selection of the halon replacement extinguishant from among the three tested. The T2 Team was composed of representatives from the Air Force, Navy, Army, and FAA and was responsible for the selection of the halon replacement extinguishant with assistance from industry and aircraft customer representatives. Phase II testing used the parameters (factors) that were found in Phase I to be most significant in determining extinguishant quantities.

Phase III of the Halon Replacement Program for Aviation - Establishment of Design Criteria Methodologies - was conducted in FY95. Phase III established design criteria for the new extinguishant in the engine nacelle application. The outcome of this phase was design formulas for use in sizing fire-extinguishing systems with the new extinguishant.

The test series conducted during this phase of the overall test program consisted of three basic 16-Run Plackett-Burman two-level fractional factorial experimental matrix designs (L16), one L16 matrix for each candidate extinguishant. This design provides for a level III resolution, meaning that there will be no main effects or fire zone parameters confounded (i.e., have its significance complicated) with other main effects. However, main effects will be confounded with two-factor interaction (the synergistic effects of two factors on the response variable) or

higher-order interactions of factors. Since the primary purpose of Phase II was to compare the three extinguishants, the factor Extinguishant was "blocked" out to isolate the effect of the extinguishant on the response variable (which was the amount of extinguishant required to extinguish the fire). Therefore, Extinguishant was not confounded with any higher order interactions of factors. "Blocked" implies that a range of experiments was independently run against each extinguishant (in essence, each extinguishant was tested under identical conditions).

Based on analysis of the logarithmically transformed data, Phase I testing had shown that the five most unquestionably significant parameters (factors) involved in engine nacelle fire extinguishment were:

- Surface Temperature
- Clearance
- Air Temperature
- Extinguishant
- Fuel Temperature

Accordingly, these parameters (factors) were used in Phase II. In addition, discussion with experts in the field of aircraft fires, as well as consideration of other issues and information (e.g., the contribution of potential two-factor interactions) resulted in the inclusion of four additional parameters in the test matrix:

- Fire Location in Nacelle
- Fuel Type
- Internal Ventilation Airflow
- Extinguishant Bottle Temperature

These parameters and their level settings are shown below. The tests were blocked on the three extinguishants mentioned previously as the candidate extinguishants.

Table 1. Phase II Varied Parameters and Levels

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Air Temperature	ATMP	100°F	275°F
Clearance (voided distance between outer nacelle and engine core)	CLEAR	6 inches	12 inches
Extinguishant Bottle Temperature	BTMP	-55°F	160°F
Fire Location in Nacelle	LOCA	Bottom	Top
Fuel	FUEL	MIL-H-83282	JP-8
Fuel Temperature	FTMP	100°F	200°F (83282) 325°F (JP-8)
Internal Ventilation Airflow	INTE	0.9 lb/s	2.7 lb/s
Surface Temperature	STMP	175°F	1300°F

The remaining parameters were set at a worst-case level with respect to extinguishant quantities required, or in some cases, a feasible level for experimentation at the facility. These parameters and the setting of each are shown in Table 2.

Table 2. Phase II Constant Parameters and Levels

PARAMETER	SYMBOL	SETTING
Extinguishant Bottle Pressure	BPRS	400 psia (@70°F)
Clutter (simulated by ribs protruding from core and nacelle)	CLUT	2 inch high ribs
Configuration* (simulating longer or shorter nacelles)	CONF	Short (123 in.)
Extinguishant Discharge Location	ALOC	Side
Extinguishant Distribution (either use of a simple distribution tube or "dumped" directly into the outer nacelle)	DIST	Dump
Preburn Time	PREB	20 sec
Ventilation Air Pressure	APRS	14.5 psia

* Defined as the distance from the extinguishant insertion point to the downstream flange at the end of the test fixture.

A series of baseline tests was conducted prior to extinguishant testing to ensure that a fire could be achieved and extinguished under every set of matrix conditions. Baseline tests were conducted with fire extinguisher parameters, fire "quality" or severity parameters, various fixtures, and airflow parameters. In addition, checklists were developed which would ensure that the test procedures would be easily and accurately duplicated in order to protect the integrity of the data for this test series.

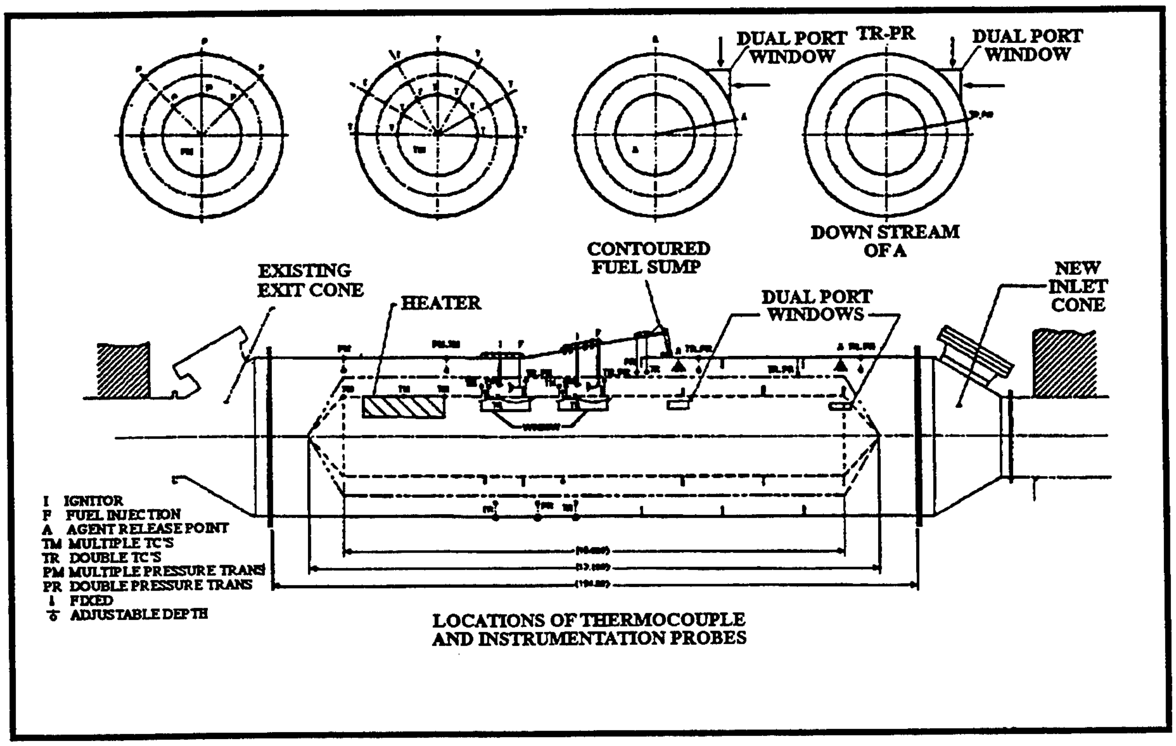

Figure 1. Adjustable Test Fixture

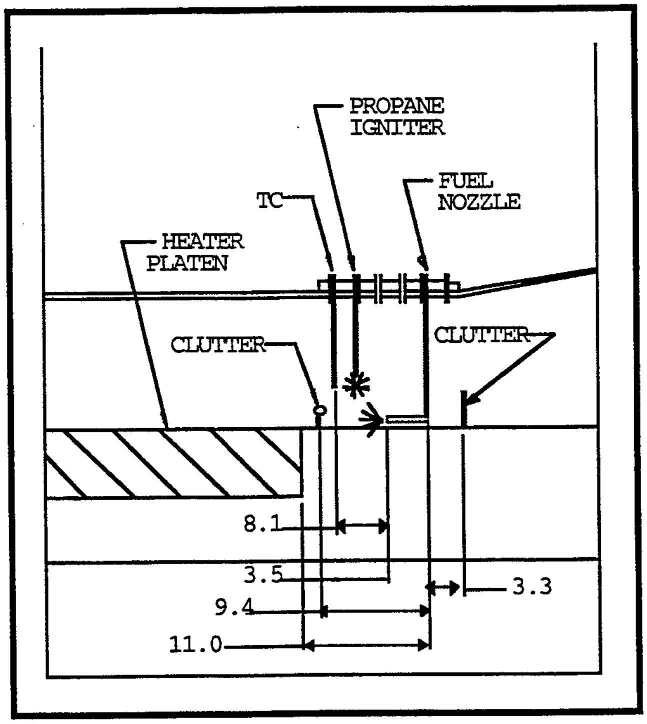

Figure 2. Close View of Clutter Around Fire Point

Results of the Phase II testing are presented in Table 3.

Table 3. Phase II Engine Nacelle Test Matrix

	RUN	FUEL	LOCA	STMP (°F)	CLEAR	FTMP (°F)	ATMP (°F)	INTE (lb/s)	BTMP (°F)	AMNT (lb)
	1	83282	BOT	175	LOW	100	100	0.9	-55	1.875
	2	JP-8	BOT	175	LOW	100	275	2.7	160	1.375
	3	83282	TOP	175	LOW	200	100	2.7	160	0.940
	4	JP-8	TOP	175	LOW	325	275	0.9	-55	0.940
	5	83282	BOT	1300	LOW	200	275	2.7	-55	3.750
H	6	JP-8	BOT	1300	LOW	325	100	0.9	160	11.000
F	7	83282	TOP	1300	LOW	100	275	0.9	160	9.000
C	8	JP-8	TOP	1300	LOW	100	100	2.7	-55	20.690
2	9	83282	BOT	175	HIGH	200	275	0.9	160	4.500
2	10	JP-8	BOT	175	HIGH	325	100	2.7	-55	3.250
7	11	83282	TOP	175	HIGH	100	275	2.7	-55	1.875
	12	JP-8	TOP	175	HIGH	100	100	0.9	160	1.875
	13	83282	BOT	1300	HIGH	100	100	2.7	160	26.940
	14	JP-8	BOT	1300	HIGH	100	275	0.9	-55	2.250
	15	83282	TOP	1300	HIGH	200	100	0.9	-55	20.690
	16	JP-8	TOP	1300	HIGH	325	275	2.7	160	2.250
	17	83282	BOT	175	LOW	100	100	0.9	-55	2.250
	18	JP-8	BOT	175	LOW	100	275	2.7	160	0.815
	19	83282	TOP	175	LOW	200	100	2.7	160	0.815
	20	JP-8	TOP	175	LOW	325	275	0.9	-55	1.125
	21	83282	BOT	1300	LOW	200	275	2.7	-55	11.000
H	22	JP-8	BOT	1300	LOW	325	100	0.9	160	11.000
F	23	83282	TOP	1300	LOW	100	275	0.9	160	4.500
C	24	JP-8	TOP	1300	LOW	100	100	2.7	-55	2.750
1	25	83282	BOT	175	HIGH	200	275	0.9	160	2.250
2	26	JP-8	BOT	175	HIGH	325	100	2.7	-55	2.250
5	27	83282	TOP	175	HIGH	100	275	2.7	-55	1.625
	28	JP-8	TOP	175	HIGH	100	100	0.9	160	2.750
	29	83282	BOT	1300	HIGH	100	100	2.7	160	25.190
	30	JP-8	BOT	1300	HIGH	100	275	0.9	-55	4.500
	31	83282	TOP	1300	HIGH	200	100	0.9	-55	23.440
	32	JP-8	TOP	1300	HIGH	325	275	2.7	160	2.250
	33	83282	BOT	175	LOW	100	100	0.9	-55	1.875
	34	JP-8	BOT	175	LOW	100	275	2.7	160	1.375
	35	83282	TOP	175	LOW	200	100	2.7	160	1.125
	36	JP-8	TOP	175	LOW	325	275	0.9	-55	1.125
	37	83282	BOT	1300	LOW	200	275	2.7	-55	4.500
	38	JP-8	BOT	1300	LOW	325	100	0.9	160	4.500
C	39	83282	TOP	1300	LOW	100	275	0.9	160	0.815
F	40	JP-8	TOP	1300	LOW	100	100	2.7	-55	4.500
3	41	83282	BOT	175	HIGH	200	275	0.9	160	0.940
I	42	JP-8	BOT	175	HIGH	325	100	2.7	-55	1.125
	43	83282	TOP	175	HIGH	100	275	2.7	-55	0.470
	44	JP-8	TOP	175	HIGH	100	100	0.9	160	0.563
	45	83282	BOT	1300	HIGH	100	100	2.7	160	6.500
	46	JP-8	BOT	1300	HIGH	100	275	0.9	-55	0.940
	47	83282	TOP	1300	HIGH	200	100	0.9	-55	1.625
	48	JP-8	TOP	1300	HIGH	325	275	2.7	160	1.375

Phase II testing clearly showed that CF_3I was the superior extinguishant, requiring on average only 34% of the amount of the next best extinguishant (HFC-125) to extinguish the fires. Results of Phase II testing are shown in Table 4.

Table 4. Average Weight of Extinguishants (lbs) - Phase II Test Matrix

EXTINGUISHANT	16 TESTS
HFC-227ea	7.075
HFC-125	6.157
CF_3I	2.085

The data generated under this test program and documented in this report were presented to the Technology Transition (T2) Team in October 1994. This meeting was held at the National Institute of Standards and Technology. At this meeting, members of the T2 Team reviewed all the data related to the candidate extinguishants. These data included information on toxicity, costs, and corrosiveness, as well as the data from this test program. The objective of the T2 Team was to select the halon replacement extinguishant from among the three candidate extinguishants. This extinguishant was then carried forward for an extended test series in order to develop design equations for the new extinguishant in Phase III of the Halon Replacement Program for Aviation.

Although CF_3I was superior in extinguishing performance among the extinguishants tested, HFC-125 was selected by the T2 Team as the extinguishant to take forward into Phase III. HFC-125 was selected due to questions of cardiotoxicity raised about CF_3I based on recent data, and the superior cold temperature distribution capability and "Halon 1301-like" flow and discharge behavior of HFC-125, as well as an observed slight performance advantage of HFC-227ea.

1.0 INTRODUCTION

The Clean Air Act Amendments (CAAA) of 1990 and U.S. Environmental Protection Agency (EPA) rules limit U.S. production of ozone depleting substances (ODS). These actions carry out the United States' obligations under the "Montreal Protocol on Substances that Deplete the Ozone Layer", an international treaty ratified by the Senate in December 1988, limiting global production of such chemicals. Subsequent international and national legislation has dictated the phase-out of the production of such chemicals. In response, industry producers have ceased production as of 1 January 1994. Other substances are likely to be added in the future. These restrictions were put in place because of data showing that the atmospheric chlorine loading caused by these chemicals correlates to depletion of the earth's protective stratospheric ozone layer. Stratospheric ozone depletion is predicted to have a significant adverse global impact on human health, climate, and natural environmental systems.

Some of the most important of the ODS chemicals are the halons, especially Halon 1301. The importance of halons derives from the fact that they are used as the primary fire-extinguishing chemical for all aviation use, including military and civilian aircraft, for engine nacelle and dry bay protection. The concern for engine nacelle fires centers on the space between the engine cowling and the engine core, where fuel lines, hydraulic lines, and other protuberances and equipment are attached to the core and can rupture or leak fuel and be ignited by sparks or hot engine surfaces.

Halons have been used as fire-extinguishing extinguishants in military and commercial aircraft since the late 1940s. After many years of operational experience, Halon 1301 (CF_3Br) emerged as the dominant extinguishant for aircraft (with some Air Force use of Halons 1202 and 1011). This is due primarily to the wide range of applications to which Halon 1301 is suited, as well as low toxicity and efficiency. However, increasing environmental concerns with ozone depletion have resulted in a mandate to discontinue its further implementation.

A decision was made by the U.S. Air Force in 1992 to develop a "nonozone depleting solution" for on-board aircraft fire extinguishing by 1995. This timeline was dictated by the program schedule of the F-22 fighter, so that this alternative solution could be considered for their implementation. A program for evaluating and identifying alternative extinguishing extinguishants that would be commercially available at that time was developed by the Air Force's Wright Laboratory. This program - The Halon Replacement Program for Aviation - was subsequently expanded in scope to include the requirements of all U.S. military and commercial aircraft engine nacelle and dry bay applications and was sponsored by the U.S. Air Force, Navy, Army, and Federal Aviation Administration. A Department of Defense Halon Alternatives Steering Group was established to oversee this and other similar programs.

A Small Business Innovative Research (SBIR) effort funded by Wright-Patterson Air Force Base investigated a total of 600 chemicals with physical properties similar to the halons as potential replacements. These potential replacement chemicals were investigated for toxicity, physical traits, and fire-fighting effectiveness to determine which had the potential to meet aviation requirements. It was determined that ten chemicals had characteristics acceptable for aircraft use and the capability to generate the necessary supplemental data within the required program timelines. To these ten, the Air Force added two from other data sources. A screening program to reduce this list of 12 to the three best for full-scale testing was conducted by the National Institute of Standards and Technology (NIST). Concurrently with this NIST testing, Phase I of the Halon Replacement Program for Aviation was conducted at Wright Laboratory. Phase I was intended to identify the fire zone variables most relevant to sizing fire extinguishing systems.

There are several important considerations in replacing halon in aircraft fire protection systems. The most obvious among these are the weight and volume of the extinguishant and of the delivery equipment. Since there are severe weight and space limitations on aircraft systems, engineers may be forced to compromise fire suppression capability in order to meet a restriction on system weight. This could cause a significant decrease in aircraft and pilot survivability. These were some of the issues considered during this program.

Phase I - Operational Parameters Study - was the first of the three-phase Halon Replacement Program for Aviation. Phase I for the engine nacelle application was completed in August 1993 and is documented in a Wright Laboratory report entitled *Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application - Phase I - Operational Parameters Study*, WL-TR-95-3077, September 1995. The objective of Phase I testing was to determine which parameters (factors) in an aircraft engine nacelle fire most influence the amount of extinguishant needed to extinguish that fire.

This final report documents the work performed under Phase II - Operational Comparison of Selected Extinguishants - of the Halon Replacement Program for Aviation. This joint program was designed to find a replacement chemical extinguishant for halon as a fire-extinguishing extinguishant on board military and commercial aircraft. There are two applications considered under this program - dry bays and engine nacelles. This report deals with the engine nacelle application. An analogous series of tests was also conducted to determine a halon replacement for the dry bay application. This work was documented in a similar series of reports.

Phase II testing, which was conducted during Fiscal Year (FY) 94, represented the culmination and confluence of two independent series of experiments conducted during FY93. The first of these experiments was performed at NIST. During this period of time, NIST personnel conducted laboratory-scale screening and compatibility testing on the 12 potential replacement extinguishants. Results of the NIST testing are documented in NIST SP 861, *Evaluation of Alternative In-Flight Fire Suppressants for Full Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays*, April 1994. The second simultaneous test series conducted during this FY93 time frame was the Phase I - Operational Parameters Study - mentioned above.

All Phase II engine testing was performed by the Aircraft Survivability and Safety Branch of Wright Laboratory (WL/FIVS) using the Aircraft Engine Nacelle Test Simulator (AEN) at Wright-Patterson Air Force Base (WPAFB), Ohio. The AEN is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine and to test the effectiveness of the methods used to prevent, detect and extinguish fires in that area. The test fixture developed for the facility is configured to represent an entire engine nacelle and can simulate a full 360° airflow field and can recreate realistic helical extinguishant distribution. The fixture is designed to be universal in representation and reconfigurable to simulate a wide variety of fighter, transport and helicopter engine nacelle shapes and sizes. The zone volume was adjusted by a wide or narrow internal cylidrical insert that represented the engine casing. The outer dimension of the test fixture remained constant. The compartment configuration (associated with various nacelle lengths) was controlled by placing the extinguishant release inlet at two different locations within the nacelle to simulate long and short nacelles. A standard clutter configuration, composed of longitudinal and circumferential baffles, was needed around the fire zone to act as a flame holder (bluff body stabilization region) and simulate structural ribs and other engine components that are normally found in engine nacelles. Removable clutter of a similar fashion was used upstream in some cases to realistically hinder extinguishant distribution. Engine case temperature simulation was provided by heating elements within a localized heater platen near the aft end of the engine. Air delivery and

conditioning equipment allow for the simulation of atmospheric and above- and below-atmospheric test pressures. In addition, controllable heating of the ventilation air was provided by duct heaters located upstream.

On 7 October 1993, WL and NIST personnel presented the results of their Phase I testing in a meeting held at Wright-Patterson Air Force Base, Ohio. Attendees included members of the Technology Transition (T2) Team. These team members, representing the Air Force, Navy, Army, and Federal Aviation Administration, were responsible for the selection of the halon replacement extinguishant. Also in attendance were personnel from the various operational commands and Wright Laboratory as well as Government contractors, such as airframers and fire extinguisher manufacturers. The purpose of the meeting was to evaluate the data and select the three most promising candidates with which to proceed to Phase II comparison testing. After presentation and discussion of the data, the T2 Team selected the following extinguishants:

- HFC-227ea (Trade Name - FM200)
- HFC-125 (Trade Name - FE25 and others)
- CF_3I (Trade Name - Iodoguard or Triodide)

The full-scale operational comparison testing of these three candidate extinguishants is the focus of this report.

Phase III of the Halon Replacement Program for Aviation - Establishment of Design Criteria Methodologies - was conducted in FY95. Phase III established design criteria for the new extinguishant in the engine nacelle application. The outcome of this phase was design formulas for use in sizing fire-extinguishing systems with the new extinguishant.

Although CF_3I was superior in extinguishing performance among the extinguishants tested, HFC-125 was selected by the T2 Team as the extinguishant to take forward into Phase III. HFC-125 was selected due to questions of cardiotoxicity raised about CF_3I based on recent data, and the superior cold temperature distribution capability and "Halon 1301-like" flow and discharge behavior of HFC-125, as well as an observed slight performance advantage of HFC-227ea.

2.0 TEST OBJECTIVE

The objective of Phase II testing for the Halon Replacement Program for Aviation was to develop full-scale live fire test data comparing the three selected candidate replacement extinguishants. The data generated under this test program were presented to the T2 Team to aid in the ultimate selection of the halon replacement extinguishant from among the three tested.

3.0 APPROACH

This phase of the overall test program utilized the results of Phase I testing which showed which individual parameters were the most important in an aircraft engine nacelle fire environment. Other parameters were added to the Phase II test matrix based on their secondary effect on the fire suppression process in concert with other variables. These parameters are discussed below.

3.1 Phase II Test Series Parameters

3.1.1 Varied Parameters

The results of Phase I - Operational Parameters Study - were presented to members of an ad hoc Phase II Test Planning Working Group at two meetings in August 1994. Members of this group included experts in the fields of fire protection, aircraft survivability, and statistical analysis. Based on review of the Phase I results, the group determined that five factors (parameters) were the most individually significant of the 16 investigated. These five were:

- Surface Temperature
- Extinguishant
- Clearance
- Fuel Temperature
- Air Temperature

These factors were incorporated into the Phase II test matrix design.

Further discussion of the Phase I test results, and consideration of the observed potential for two-factor interactions, led to the inclusion of four additional factors into the test matrix. These factors were:

- Fire Location
- Internal Ventilation Airflow
- Fuel
- Extinguishant Bottle Temperature

Rationale for the inclusion of these four additional factors is presented below.

3.1.1.1 Fire Location

During pre-Phase I testing with the 360° annulus (full nacelle simulator), one of the extinguishants that was being used - perfluorohexane - has a very high boiling point and therefore does not vaporize and distribute well in a "total flood" application; as a result, it was observed that it had difficulty in extinguishing fires when the discharge location was on the opposite side of the core from the fire location. This necessitated removing this extinguishant from the test matrix and replacing it with HFC-227ea. The factor Fire Location was included in the Phase II test matrix to insure that such a characteristic of any of the candidate extinguishants, or any degradation in its performance, would be identified. This factor was also identified in Phase I testing as a possible contributor to a significant two-factor interaction.

3.1.1.2 Internal Ventilation Airflow

This factor was included in the test matrix in order to investigate the effects of higher mass air flows.

3.1.1.3 Fuel

During Phase I testing, hot surface re-ignition became an important issue. Inclusion of the factor Fuel in the Phase II test matrix was an attempt to investigate this phenomenon further. In particular, MIL-H-83282 hydraulic fluid appeared to remain as a residue longer than the JP-8, therefore having a greater impact on the re-ignition question. This factor was also identified in Phase I testing as a possible contributor to a significant two-factor interaction.

3.1.1.4 Extinguishant Bottle Temperature

The three extinguishants that were used in Phase II testing had the potential for completely different temperature characteristics than the extinguishants in Phase I with different distribution and overall effectiveness properties at low temperatures. For this reason, Extinguishant Bottle Temperature remained a factor in Phase II testing. However, one change was made concerning the bottle pressure. The three extinguishants were charged to test pressure while at 70°F and then heated or cooled to the appropriate test temperature. The pressure at this test temperature was noted for each chemical and the extinguishant was charged to this pressure at that respective temperature in all subsequent tests.

The eight factors - Surface Temperature, Clearance, Fuel Temperature, Air Temperature, Fire Location, Internal Airflow, Fuel, and Extinguishant Bottle Temperature - were those varied in Phase II testing. The Phase II test matrix was blocked on the remaining factor - Extinguishant, which allows a head-to-head comparison of the extinguishants under identical tests. The blocking concept is presented in greater detail in paragraph 3.2. These parameters and their level settings are shown below in Table 3-1.

Table 3-1. Phase II Varied Parameters and Levels

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Surface Temperature	STMP	175°F	1300°F
Clearance (voided distance between engine core and outer nacelle)	CLEAR	6 inches	12 inches
Fuel Temperature	FTMP	100°F	200°F (83282) 325°F (JP-8)
Air Temperature	ATMP	100°F	275°F
Fire Location	LOCA	Bottom	Top
Internal Ventilation Airflow	INTE	0.9 lb/s	2.7 lb/s
Fuel	FUEL	MIL-H-83282	JP-8
Extinguishant Bottle Temperature	BTMP	-55°F	160°F

3.1.2 Constant Parameters

The remaining factors were set at a worst-case level, or in some cases, a feasible level within test facility constraints. Because of limitations on the test matrix size due to schedule constraints, it was decided that investigation of Preburn Time would be more appropriate in Phase III of the test program, since it was determined that it would not be a discriminator in the performance of the extinguishants under consideration in Phase II. Preburn Time was therefore held constant in Phase II. The constant factors and their settings are presented in Table 3-2.

Table 3-2. Phase II Constant Parameters and Levels

PARAMETER	SYMBOL	SETTING
Preburn Time	PREB	20 sec
Extinguishant Discharge Location	ALOC	Side
Extinguishant Bottle Pressure	BPRS	400 psia (@70°F)
Configuration* (long or short nacelles simulated)	CONF	Short (123 in.)
Clutter (height of ribs on core and nacelle)	CLUT	High (2 in.)
Extinguishant Distribution (distribution tube or dumped directly into nacelle)	DIST	Dump
Air Pressure	APRS	14.5 psia

*Defined as the distance from the extinguishant insertion point to the downstream flange.

3.2 Test Matrix

Given the eight factors identified previously as those to be varied in Phase II, a test matrix was designed. This matrix is shown in Table 3-3.

Table 3-3. Phase II Engine Nacelle Test Matrix

	RUN	FUEL	LOCA	STMP (°F)	CLEAR	FTMP (°F)	ATMP (°F)	INTE (lb/s)	BTMP (°F)
	1	83282	BOT	175	LOW	100	100	0.9	-55
	2	JP-8	BOT	175	LOW	100	275	2.7	160
	3	83282	TOP	175	LOW	200	100	2.7	160
	4	JP-8	TOP	175	LOW	325	275	0.9	-55
	5	83282	BOT	1300	LOW	200	275	2.7	-55
H	6	JP-8	BOT	1300	LOW	325	100	0.9	160
F	7	83282	TOP	1300	LOW	100	275	0.9	160
C	8	JP-8	TOP	1300	LOW	100	100	2.7	-55
2	9	83282	BOT	175	HIGH	200	275	0.9	160
2	10	JP-8	BOT	175	HIGH	325	100	2.7	-55
7	11	83282	TOP	175	HIGH	100	275	2.7	-55
	12	JP-8	TOP	175	HIGH	100	100	0.9	160
	13	83282	BOT	1300	HIGH	100	100	2.7	160
	14	JP-8	BOT	1300	HIGH	100	275	0.9	-55
	15	83282	TOP	1300	HIGH	200	100	0.9	-55
	16	JP-8	TOP	1300	HIGH	325	275	2.7	160
	17	83282	BOT	175	LOW	100	100	0.9	-55
	18	JP-8	BOT	175	LOW	100	275	2.7	160
	19	83282	TOP	175	LOW	200	100	2.7	160
	20	JP-8	TOP	175	LOW	325	275	0.9	-55
	21	83282	BOT	1300	LOW	200	275	2.7	-55
H	22	JP-8	BOT	1300	LOW	325	100	0.9	160
F	23	83282	TOP	1300	LOW	100	275	0.9	160
C	24	JP-8	TOP	1300	LOW	100	100	2.7	-55
I	25	83282	BOT	175	HIGH	200	275	0.9	160
2	26	JP-8	BOT	175	HIGH	325	100	2.7	-55
5	27	83282	TOP	175	HIGH	100	275	2.7	-55
	28	JP-8	TOP	175	HIGH	100	100	0.9	160
	29	83282	BOT	1300	HIGH	100	100	2.7	160
	30	JP-8	BOT	1300	HIGH	100	275	0.9	-55
	31	83282	TOP	1300	HIGH	200	100	0.9	-55
	32	JP-8	TOP	1300	HIGH	325	275	2.7	160
	33	83282	BOT	175	LOW	100	100	0.9	-55
	34	JP-8	BOT	175	LOW	100	275	2.7	160
	35	83282	TOP	175	LOW	200	100	2.7	160
	36	JP-8	TOP	175	LOW	325	275	0.9	-55
	37	83282	BOT	1300	LOW	200	275	2.7	-55
	38	JP-8	BOT	1300	LOW	325	100	0.9	160
C	39	83282	TOP	1300	LOW	100	275	0.9	160
F	40	JP-8	TOP	1300	LOW	100	100	2.7	-55
3	41	83282	BOT	175	HIGH	200	275	0.9	160
I	42	JP-8	BOT	175	HIGH	325	100	2.7	-55
	43	83282	TOP	175	HIGH	100	275	2.7	-55
	44	JP-8	TOP	175	HIGH	100	100	0.9	160
	45	83282	BOT	1300	HIGH	100	100	2.7	160
	46	JP-8	BOT	1300	HIGH	100	275	0.9	-55
	47	83282	TOP	1300	HIGH	200	100	0.9	-55
	48	JP-8	TOP	1300	HIGH	325	275	2.7	160

Three basic 16-Run Plackett-Burman two-level fractional factorial designs (L16) were used for this test series, one L16 for each extinguishant. This design provides for a level III resolution, meaning that there will be no main effects confounded (i.e., have its significance complicated) with other main effects. However, main effects will be confounded with two-factor interaction (the synergistic effects of two factors on the response variable) or higher-order interactions.

The primary purpose of Phase II was to compare the performance of the three extinguishants to determine which performed the best on average for overall use. To help achieve this goal, the factor Extinguishant was "blocked" out to isolate the effect of the extinguishant on the response variable (amount of extinguishant required to extinguish the fire). Therefore, the factor Extinguishant was not confounded with any higher order interactions. "Blocked" implies that a range of experiments were independently run against each extinguishant, as shown in Table 3-3 above.

3.3 Amount of Extinguishant

The most difficult consideration in the DOX design was the determination of the response variable (amount of extinguishant to extinguish the fire). It is virtually impossible to directly measure this variable in its application directly to the fire during the test. To address this problem, a bracketing procedure was devised (Figure 3-1) which used an iterative process to narrow down the precise minimum amount of extinguishant required to extinguish the fire. In all tests, a minimum of four iterations was used, each adjusting the quantity of extinguishant used to determine the threshold of extinguishant mass. This methodology provided an uncertainty of ±6.25%.

As an example, using the bracketing protocol in Figure 3-1, say an experimental run began with 2 pounds of extinguishant. If the 2 pounds of extinguishant extinguished the fire in this run, its weight would be halved for the second run. If Test 2 did not extinguish the fire, then the third test run would use the average between the extinguishant weights used in Tests 1 and 2, in this case, Test 3 would use 1.5 pounds of extinguishant. If the fire was extinguished in Test 3, then the amount of extinguishment used in Test 4 would be decreased by 25% of the difference in weights used in Tests 1 and 2, or in this case, .25 pounds (.25 x (2 - 1 pounds)). So Test 4 would use 1.25 pounds of extinguishant. Finally, if the fourth test weight extinguished the fire, then the extinguishant weight would be decreased by (.125 x (Test 1 - Test 2)), or .125 pounds. Therefore, the final weight of extinguishant, by this bracketing procedure, is 1.125 pounds.

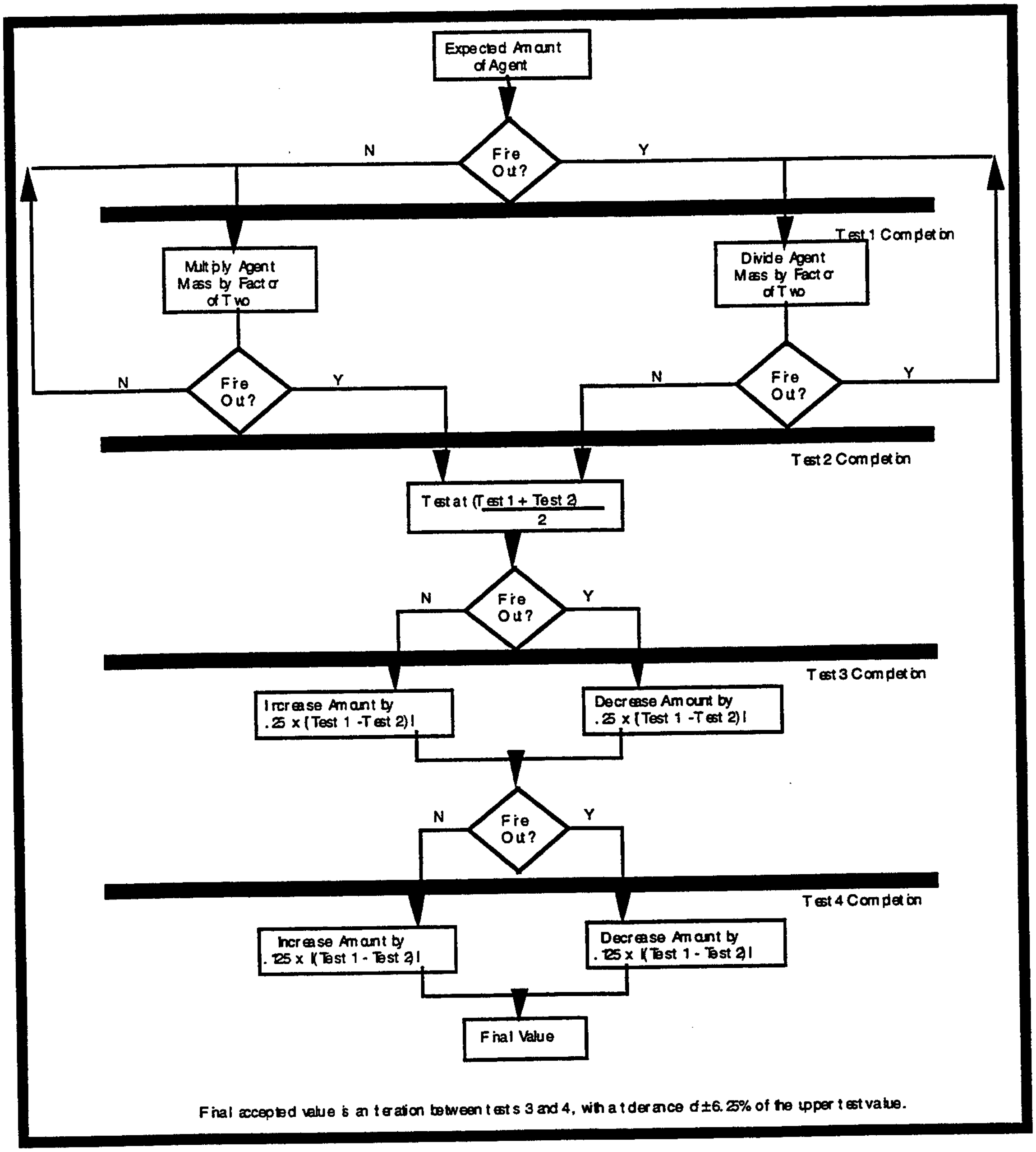

Figure 3-1. Bracketing Procedure

3.4 Test Article Configuration

3.4.1 Aircraft Engine Nacelle Fire Test Simulator

The evaluation of the replacement fire extinguishing extinguishants for the aircraft engine nacelle application was performed in the Aircraft Engine Nacelle Fire Test Simulator (AENFTS or AEN) located at Wright-Patterson Air Force Base, Ohio. The AEN is a ground test facility designed to simulate the fire hazards which exist in the annular compartment around an aircraft engine ("nacelle"), and to test the effectiveness of the methods used to prevent, detect and extinguish fires in that area. This facility includes air delivery and conditioning equipment

designed to simulate engine compartment ventilation air flow, a test section within which fire testing may be safely conducted, and an exhaust system which can cool the combustion products and scrub them sufficiently to allow their release into the atmosphere. Electrical heaters were used during the program to provide a hot surface area on the inserted engine core simulation surface.

3.4.2 Engine Nacelle Configuration

One adjustable test fixture (Figure 3-2) was designed and fabricated for the AEN and placed "on line" in March 1994. The goal of the new fixture was to simulate a full 360° airflow field around the entire full nacelle and thus permit a realistic helical extinguishant distribution. The parameter Clearance (CLEAR) was adjusted by using a 24" diameter or a 36" diameter internal insert that represented different engine core diameters of different aircraft. The outer diameter (representing the outer nacelle) remained constant at 48". The parameter Configuration (CONF) was basically the nacelle length and was held constant by placing the extinguishant release inlet 123" from the downstream flange. A standard clutter configuration, composed of longitudinal and circumferential flanges, was needed around the fire zone to act as a flame holder. Removable clutter was used upstream in some cases to hinder extinguishant distribution.

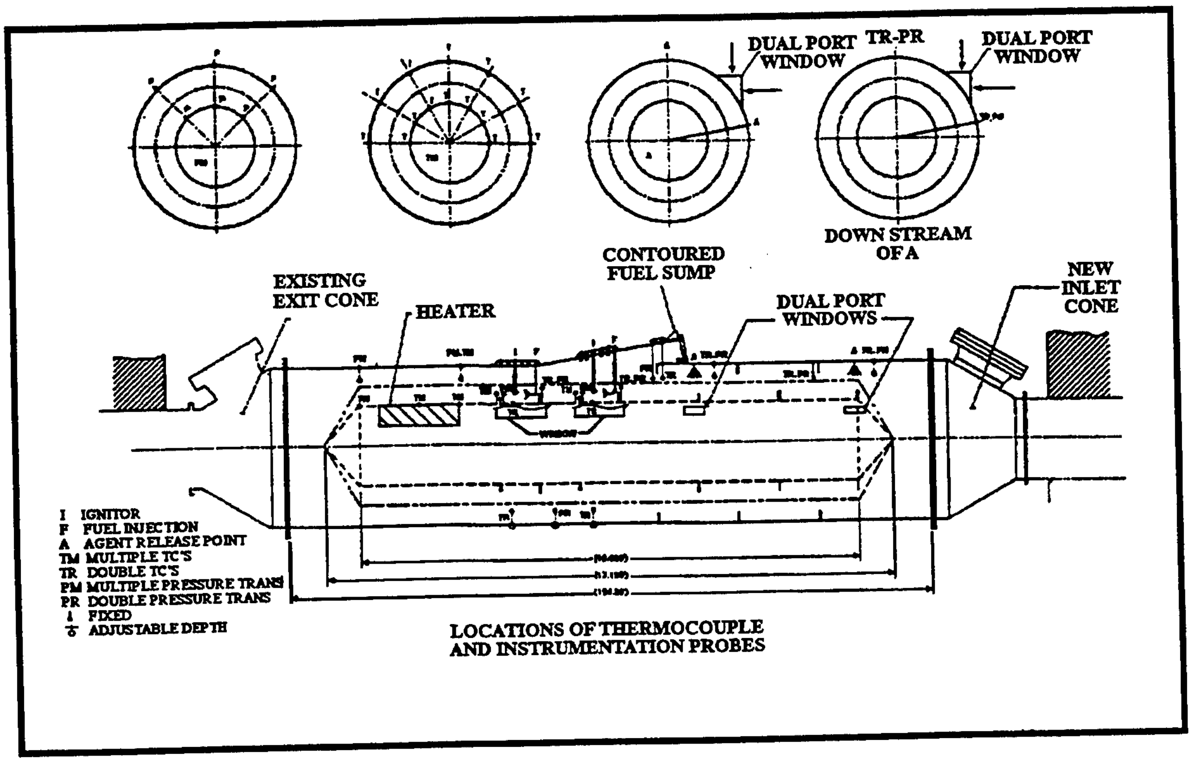

Figure 3-2. Adjustable Test Fixture

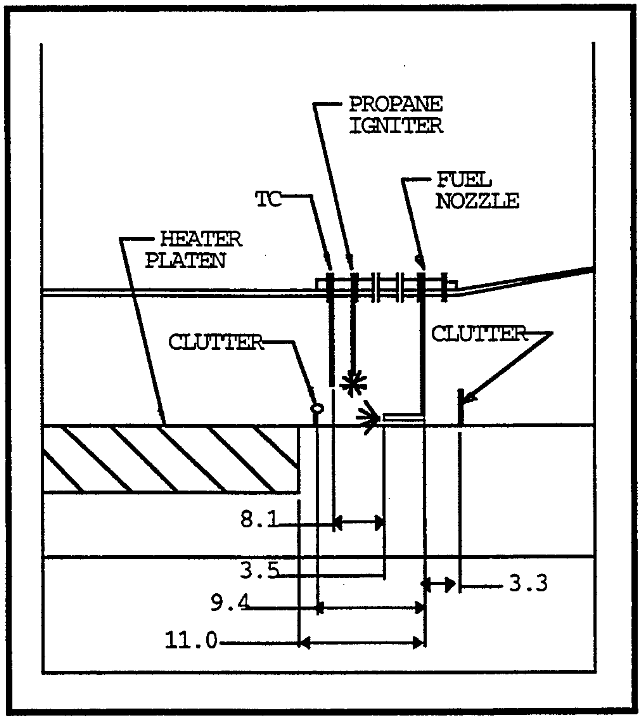

Figure 3-3. Close View of Clutter Around Fire Point

An electric heater platen was used to represent a hot operating engine section (including the "burner can") at the down-stream end of the engine core. The platen was approximately 30" long, with a 100° arc on the insert surface. The temperature is "set point" controlled at up to 1500°F.

3.4.3 Extinguishant Conditioning and Delivery

Extinguishants were delivered to the nacelle fire from a cylindrically-shaped, high pressure bottle which was equipped to either heat or chill the extinguishant. The bottle was also designed with adjustable internal volume capability to accommodate the various quantities of extinguishant desired. Heating of the extinguishant was accomplished with several electric band-type heating units mounted around the outside of the cylinder. The heaters were "set point" (set to a constant temperature) controlled and were effective for heating and maintaining the extinguishant up to 200°F. For cooling, the bottle was equipped with a flat-sided external "jacket" enclosure which was filled with dry ice. The temperature of dry ice was -127°F. Therefore, in order to maintain the cold temperature at a known fixed point such as -55°F, the band heaters were utilized to hold the desired temperature.

The volume of the extinguishant chamber was set by an adjustable floating piston which could be placed and maintained at any vertical location in the extinguishant bottle. Spacer rings were used above the piston to maintain the piston location. The extinguishant was charged and delivered from the bottom of the vertically mounted cylinder, which could accommodate from 1 ounce to 24.5 pounds of extinguishant. The charging gas was nitrogen.

Injection into the fire location in the nacelle was through a standard nozzle configuration as typically used on aircraft. A simulation of a "Y"-shaped distribution technique (See Fig. 3-4), pointed downstream was used for half of the tests to assess its influence, and the other half of the tests simply dumped the extinguishant through the side of the outer nacelle with no control of distribution. The injection location could be varied at two axial locations in the nacelle chamber.

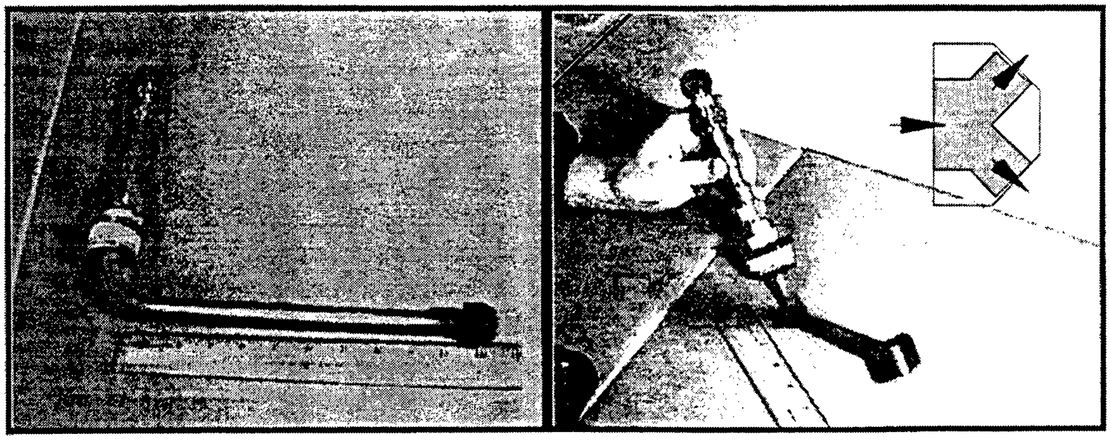

Figure 3-4. Y-Shaped Distribution Tubing

3.4.4 Extinguishants

The three extinguishants chosen for operational comparison testing were CF_3I, HFC-227ea, and HFC-125. These extinguishants were selected at the T2 Team Meeting at Wright-Patterson Air Force Base in October 1993 as the most promising halon replacement extinguishants based on lab-scale experiments using 12 candidates for consideration.

3.4.5 Airflow

Engine nacelle air delivery and conditioning allowed for the simulation of operating pressure conditions of atmospheric, above atmospheric, and below atmospheric pressures during the test. In addition, controllable heating and cooling of the air were available. The inlet air supply originated from two sources: (1) an air blower with a maximum capacity of 8,780 SCFM (11.2 pounds per second) and (2) a high pressure compressed air blow-down system with a storage capacity of 8,800 pounds of air at 2,000 psig. A flow control and vent by-pass system was used to control airflow to the engine nacelle. Standard commercial-type controllers were used to control the blower airflow. The airflow controller system consisted of a differential pressure/current transmitter, controller, current/pneumatic transducer, and a 24-inch butterfly valve with pneumatic actuator and positioner.

Figure 3-5 shows a schematic of the air exhaust subsystem, with the major components and butterfly valves. A water treatment system, which was located at ground level at the north end of the building, accepted liquids pumped from the quench/sump section and also liquids which drain or overflow from the scrubber.

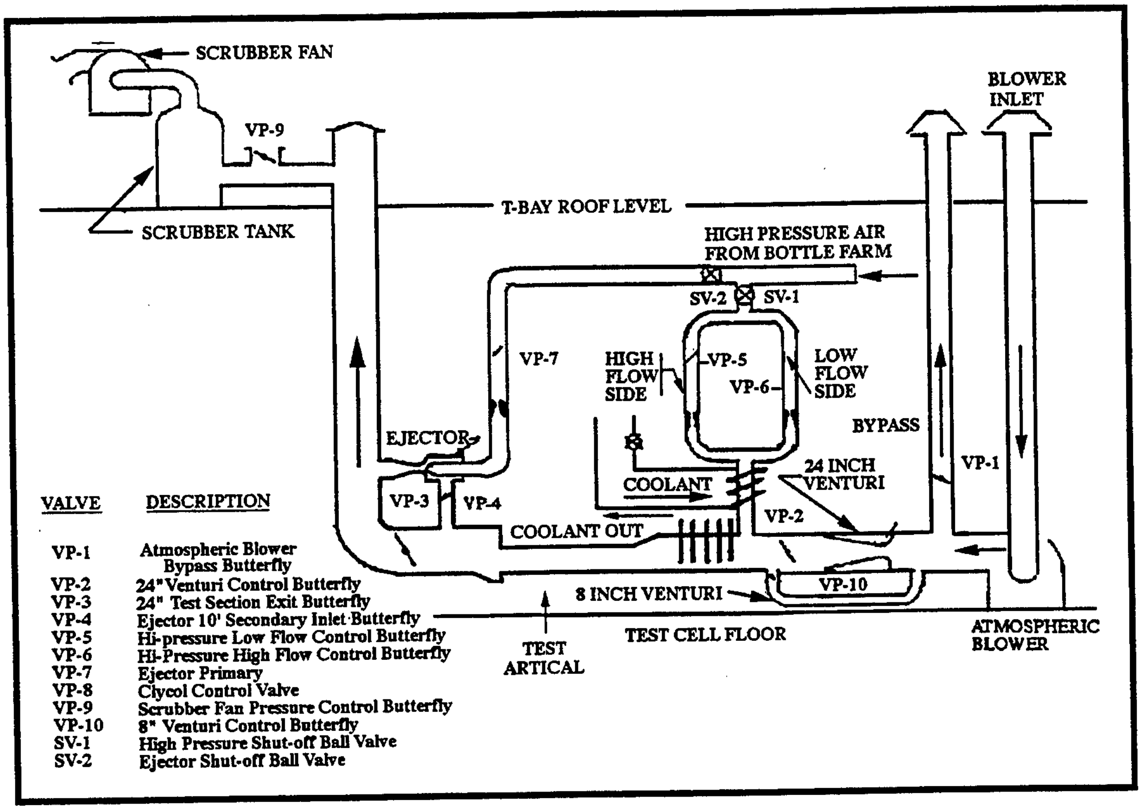

Figure 3-5. AEN Air Handling Subsystem

In addition, combustibles were separated from the water/extinguishant solution through a series of baffles in the water treatment tank where conditions were sensed for monitoring in the control room. Accumulated combustibles were manually drained into the facility waste fuel sump, and the water/chemical solution was recirculated until the water quality was on the verge of being chemically unacceptable, at which time the solution was expelled into the base sanitary sewer system.

3.4.6 Data Requirements

The primary data requirements were whether the fire was extinguished and the mass of the extinguishing extinguishant required to do so. These two data items established the measure of effectiveness used in this phase of testing. In addition, other data collected and recorded included ventilation air temperature, ventilation pressure, air mass flow rate, nacelle free volume configuration, extinguishant discharge time, fuel temperature and type, preburn time, re-ignition time, and compartment surface temperature.

Type K thermocouples were used to measure the surface temperature of the compartment walls as well as the ventilation air temperatures.

3.4.7 Data Acquisition and Recording

Static photographic support as well as limited high-speed photography support was provided by the Aeronautical System Center (ASC) Technical Photo-Department located at WPAFB.

3.4.8 Video

Video cameras were placed at two locations to view the fire through ports on the nacelle fixture. One view was from directly behind and slightly above the fuel injection nozzle looking downstream (a "bird's eye view"). The other was a side view of the fire location. The two views of each fire test were recorded on videotape which became part of the permanent record of the halon program.

3.5 Procedure

3.5.1 Qualification Testing

Prior to conducting the Phase II test matrix, it was necessary (due to the statistical experimental design process) to demonstrate that sustained fires could be achieved, and also extinguished, under all the setting conditions required by the test matrix.

3.5.2 Full-Scale Testing

Data collection worksheets for the basic L16 experimental matrix design were provided to test personnel. Table 3-4 shows a sample of these worksheets. Each extinguishant was provided its own unique data sheet. This worksheet records the LOW/HIGH level settings for each factor for each test run. Run 1 shows each factor set at its LOW level. Successive test runs vary the level of different factors as shown.

Table 3-4. Data Collection Worksheet

				STMP		FTMP	ATMP	INTE	BTMP	AMT
	RUN	FUEL	LOCA	(°F)	CLEAR	(°F)	(°F)	(lb/s)	(°F)	(lb)
	1	83282	BOT	175	LOW	100	100	0.9	-55	
	2	JP-8	BOT	175	LOW	100	275	2.7	160	
E	3	83282	TOP	175	LOW	200	100	2.7	160	
X	4	JP-8	TOP	175	LOW	325	275	0.9	-55	
T	5	83282	BOT	1300	LOW	200	275	2.7	-55	
N	6	JP-8	BOT	1300	LOW	325	100	0.9	160	
G	7	83282	TOP	1300	LOW	100	275	0.9	160	
T	8	JP-8	TOP	1300	LOW	100	100	2.7	-55	
	9	83282	BOT	175	HIGH	200	275	0.9	160	
T	10	JP-8	BOT	175	HIGH	325	100	2.7	-55	
Y	11	83282	TOP	175	HIGH	100	275	2.7	-55	
P	12	JP-8	TOP	175	HIGH	100	100	0.9	160	
E	13	83282	BOT	1300	HIGH	100	100	2.7	160	
	14	JP-8	BOT	1300	HIGH	100	275	0.9	-55	
	15	83282	TOP	1300	HIGH	200	100	0.9	-55	
	16	JP-8	TOP	1300	HIGH	325	275	2.7	160	

Each test run was repeated three times and an estimate of the precise amount of extinguishant required to extinguish the fire was obtained. This procedure was required because

of the difficulty involved in directly measuring the response variable and is previously described in paragraph 3.3 and shown in Figure 3-1.

The procedures which were followed in the conduct of Phase II testing are presented below:

1. Configure test article.
2. Charge extinguishant distribution bottle.
3. Physically leave room if fire test involved.
4. Set remaining test parameters (airflow rate, etc.).
5. Initiate data acquisition instrumentation.
6. Initiate test fire.
7. Release extinguishant after predetermined preburn time.
8. Continue JP-8 flow for 5 seconds after extinguishant release (0 seconds for MIL-H-83282). This recreates fire conditions that require the maximum protection capability provided by current halon systems (refer to Phase I report).
9. Terminate data acquisition after 45 seconds.
10. Continue, or increase, airflow to cool down test article (560°R). (This step was only included if it were the end of the day, or in any case where the engine core was to be handled, such as engine core change-out.)
11. Remove fuel from test fixture.
12. Shut down control room to prepare for next test.

A TI Programmer or equivalent was used for all critical timing events. Output response variables recorded were:

1. Amount of extinguishant used to extinguish the fire.
2. Fire intensity (thermocouple, video signal).
3. Temperature of exhaust gases.
4. CO and CO_2 in exhaust gases.
5. Time to extinguish fire (extinguishant release to fire out).
6. Suppression time - fire out to reignition - if reignition occurs.

The following sequence of pictures and diagrams illustrates a test configuration and results. Figures 3-6 through 3-9 show the engine nacelle fire with fuel spray, and the nacelle fire after the fuel spray was turned off.

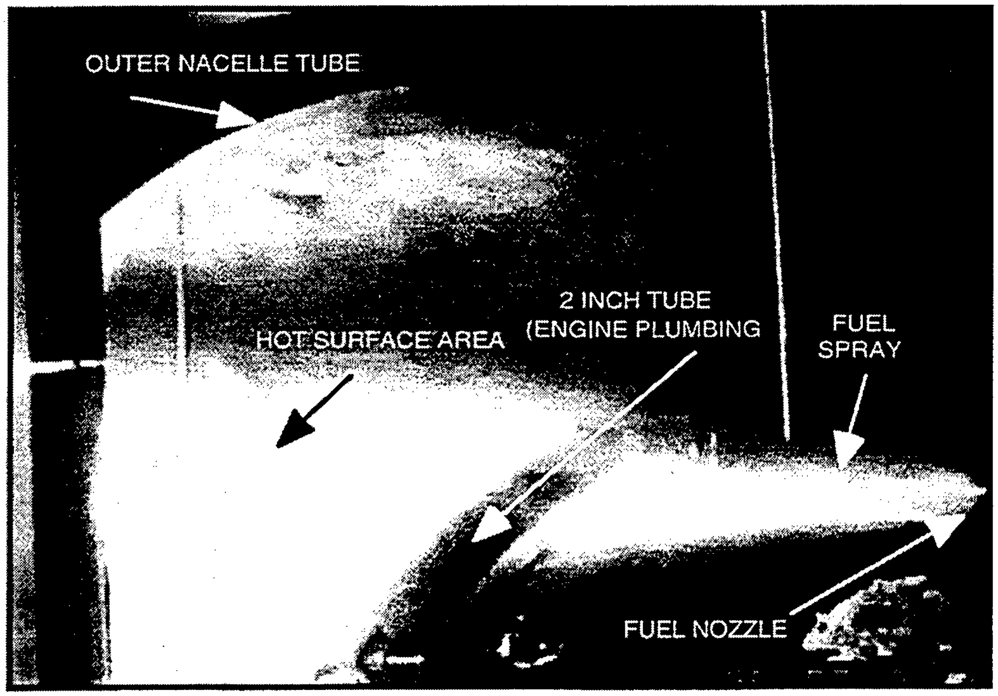

Figure 3-6. Picture of Engine Nacelle Fire With Fuel Spray

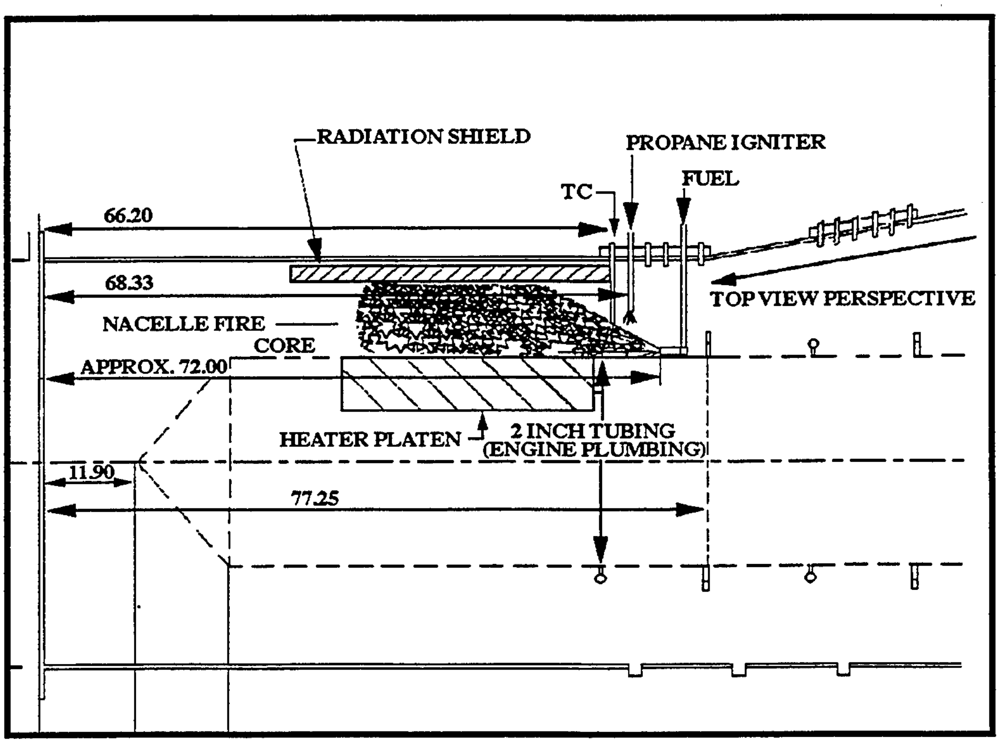

Figure 3-7. Diagram of Engine Nacelle Fire With Fuel Spray

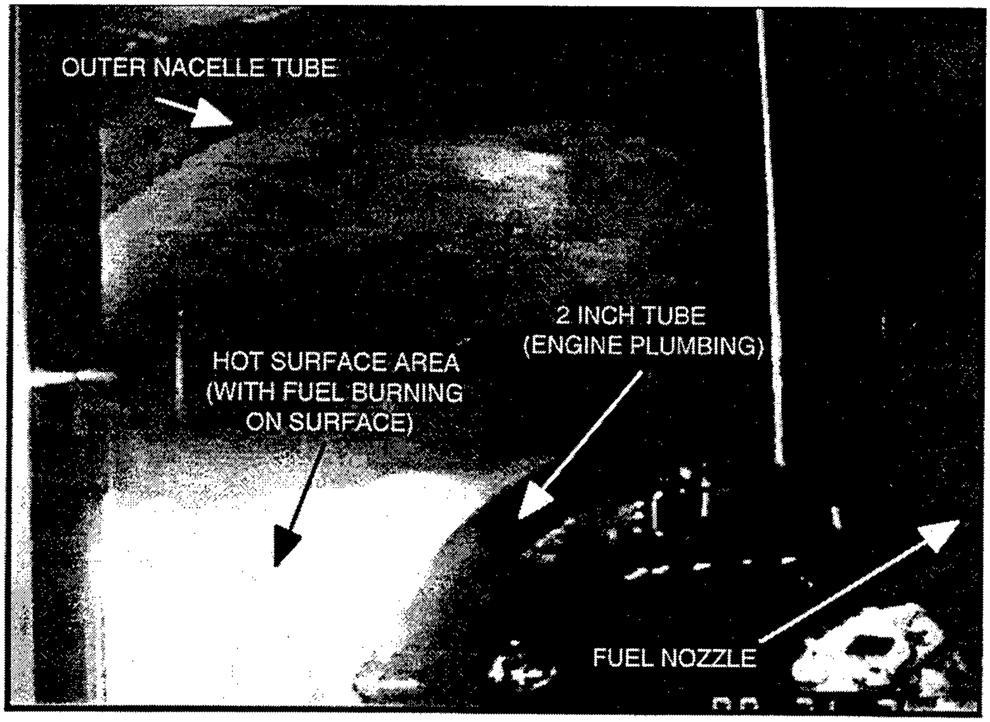

Figure 3-8. Picture of Engine Nacelle Fire With Fuel Spray Turned Off

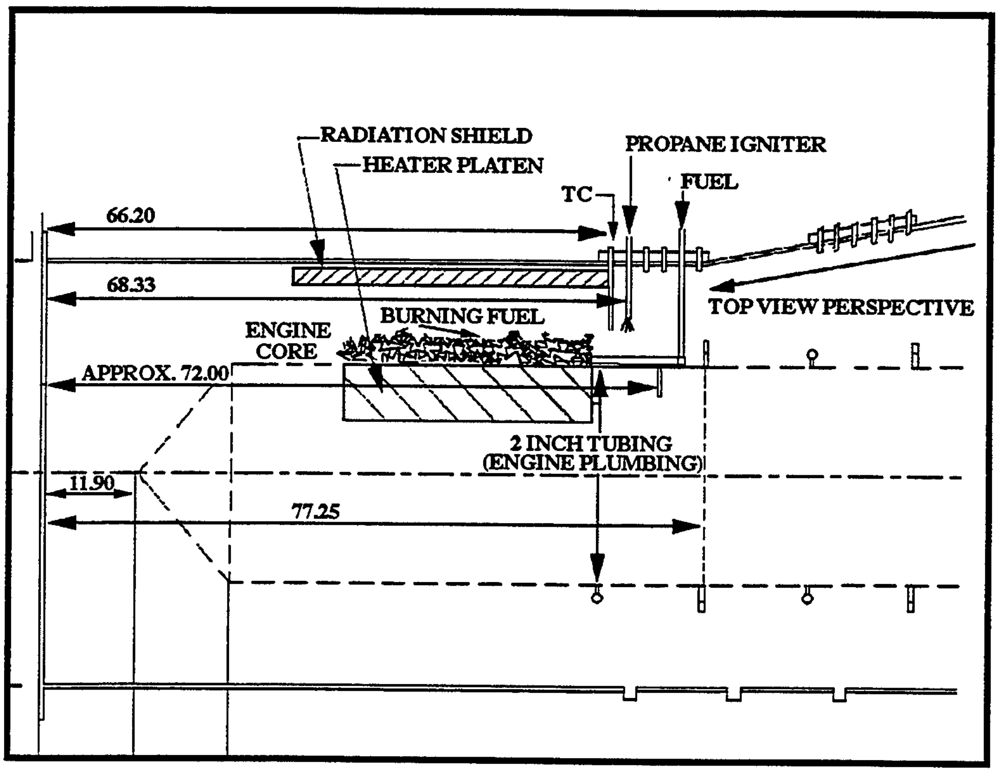

Figure 3-9. Diagram of Engine Nacelle Fire With Fuel Spray Turned Off

4.0 RESULTS

4.1 Phase II Data Analysis

Table 4-1 shows the factors that were varied in Phase II and their setting levels in the tests. Table 4-2 shows the factors that were held constant and their settings.

Table 4-1. Phase II Varied Parameters and Levels

PARAMETER	SYMBOL	LOW SETTING	HIGH SETTING
Surface Temperature	STMP	175°F	1300°F
Clearance (voided distance between outer engine nacelle and engine core)	CLEAR	6 inches	12 inches
Fuel Temperature	FTMP	100°F	200°F (83282) 325°F (JP-8)
Air Temperature	ATMP	100°F	275°F
Fire Location	LOCA	Bottom	Top
Internal Ventilation Airflow	INTE	0.9 lb/s	2.7 lb/s
Fuel	FUEL	MIL-H-83282 hydraulic fluid	JP-8
Extinguishant Temperature	BTMP	-55°F	160°F

Table 4-2. Phase II Constant Parameters and Levels

PARAMETER	SYMBOL	SETTING
Preburn Time	PREB	20 sec
Extinguishant Discharge Location (with respect to the nacelle)	ALOC	Side (of nacelle)
Extinguishant Bottle Pressure	BPRS	400 psia (@70°F)
Configuration (length of nacelle simulator)	CONF	Short
Clutter [1" (LOW) or 2" (HIGH) ribs on core, nacelle]	CLUT	High
Extinguishant Distribution (with distribution tube or dump (not tube))	DIST	Dump
Air Pressure	APRS	14.5 psia

Table 4-3 shows the 48-run Phase II Test Matrix, the factor setting levels, and the value of the response variable (extinguishant mass at extinguishment) for each run. The test matrix was "blocked" on the factor Extinguishant.

Table 4-3. Phase II Engine Nacelle Test Matrix

	RUN	FUEL	LOCA	STMP (°F)	CLEAR	FTMP (°F)	ATMP (°F)	INTE (lb/s)	BTMP (°F)	AMNT (lb)
	1	83282	BOT	175	LOW	100	100	0.9	-55	1.875
	2	JP-8	BOT	175	LOW	100	275	2.7	160	1.375
	3	83282	TOP	175	LOW	200	100	2.7	160	0.940
	4	JP-8	TOP	175	LOW	325	275	0.9	-55	0.940
	5	83282	BOT	1300	LOW	200	275	2.7	-55	3.750
H	6	JP-8	BOT	1300	LOW	325	100	0.9	160	11.000
F	7	83282	TOP	1300	LOW	100	275	0.9	160	9.000
C	8	JP-8	TOP	1300	LOW	100	100	2.7	-55	20.690
2	9	83282	BOT	175	HIGH	200	275	0.9	160	4.500
2	10	JP-8	BOT	175	HIGH	325	100	2.7	-55	3.250
7	11	83282	TOP	175	HIGH	100	275	2.7	-55	1.875
	12	JP-8	TOP	175	HIGH	100	100	0.9	160	1.875
	13	83282	BOT	1300	HIGH	100	100	2.7	160	26.940
	14	JP-8	BOT	1300	HIGH	100	275	0.9	-55	2.250
	15	83282	TOP	1300	HIGH	200	100	0.9	-55	20.690
	16	JP-8	TOP	1300	HIGH	325	275	2.7	160	2.250
	17	83282	BOT	175	LOW	100	100	0.9	-55	2.250
	18	JP-8	BOT	175	LOW	100	275	2.7	160	0.815
	19	83282	TOP	175	LOW	200	100	2.7	160	0.815
	20	JP-8	TOP	175	LOW	325	275	0.9	-55	1.125
	21	83282	BOT	1300	LOW	200	275	2.7	-55	11.000
H	22	JP-8	BOT	1300	LOW	325	100	0.9	160	11.000
F	23	83282	TOP	1300	LOW	100	275	0.9	160	4.500
C	24	JP-8	TOP	1300	LOW	100	100	2.7	-55	2.750
1	25	83282	BOT	175	HIGH	200	275	0.9	160	2.250
2	26	JP-8	BOT	175	HIGH	325	100	2.7	-55	2.250
5	27	83282	TOP	175	HIGH	100	275	2.7	-55	1.625
	28	JP-8	TOP	175	HIGH	100	100	0.9	160	2.750
	29	83282	BOT	1300	HIGH	100	100	2.7	160	25.190
	30	JP-8	BOT	1300	HIGH	100	275	0.9	-55	4.500
	31	83282	TOP	1300	HIGH	200	100	0.9	-55	23.440
	32	JP-8	TOP	1300	HIGH	325	275	2.7	160	2.250
	33	83282	BOT	175	LOW	100	100	0.9	-55	1.875
	34	JP-8	BOT	175	LOW	100	275	2.7	160	1.375
	35	83282	TOP	175	LOW	200	100	2.7	160	1.125
	36	JP-8	TOP	175	LOW	325	275	0.9	-55	1.125
	37	83282	BOT	1300	LOW	200	275	2.7	-55	4.500
	38	JP-8	BOT	1300	LOW	325	100	0.9	160	4.500
C	39	83282	TOP	1300	LOW	100	275	0.9	160	0.815
F	40	JP-8	TOP	1300	LOW	100	100	2.7	-55	4.500
3	41	83282	BOT	175	HIGH	200	275	0.9	160	0.940
I	42	JP-8	BOT	175	HIGH	325	100	2.7	-55	1.125
	43	83282	TOP	175	HIGH	100	275	2.7	-55	0.470
	44	JP-8	TOP	175	HIGH	100	100	0.9	160	0.563
	45	83282	BOT	1300	HIGH	100	100	2.7	160	6.500
	46	JP-8	BOT	1300	HIGH	100	275	0.9	-55	0.940
	47	83282	TOP	1300	HIGH	200	100	0.9	-55	1.625
	48	JP-8	TOP	1300	HIGH	325	275	2.7	160	1.375

4.1.1 Analysis of the Phase II Factorial Experiment

The data from the test matrix were analyzed by calculating effect size and sum of squares for each factor and interaction between factors, as shown in Table 4-4. The sum of squares for each factor was then expressed as a percent of the total Sum of Squares, or total variability. The larger the percentage of total variability for any factor, the stronger the indication from the data that the effect of that factor on the response variable is of sufficient size to stand out from the experimental error or "noise".

Table 4-4. Analysis of the Phase II Factorial Experiment

PARAMETER	SUM OF SQUARES	PERCENT OF TOTAL
STMP	579.957	26.022
ATMP	270.622	12.142
STMP*ATMP	249.418	11.191
EXTNGT	225.767	10.130
FUEL	107.751	4.835
STMP*FUEL	96.257	4.319
CLEAR	29.741	1.334
LOCA	15.005	0.673
INTE	3.207	0.144
FTMP	1.893	0.085
BTMP	0.372	0.017
TOTAL	2228.740*	

* The total sum of squares is larger than the value obtained by adding the effects sum of squares in the table since the total includes the sum of squares for error (See Table 4-5). This is the usual total sum of squares outputted by most statistical software packages.

The factors with the largest percentage of variability in the data explained by the factor are:

- STMP - 26%
- ATMP -12%
- EXTNGT -10%
- FUEL - 5%

The factor Extinguishant Bottle Temperature (BTMP) was again shown to not be significant in the engine nacelle fire extinguishment phenomenon with essentially 0% of the total variability explained. This is consistent with the results of Phase I testing. The remaining factors are 1% or less of the total variability explained.

Two two-factor interactions are shown in Table 4-4. The STMP*ATMP interaction has a significant percentage of total variability explained - 11% - while the STMP*FUEL interaction is marginally significant with 4% of the total variability explained.

The scree plot in Figure 4-1 graphically demonstrates the relative influences of the different fire zone factors on quantities of extinguishing extinguishant needed, as shown in Table 4-4.

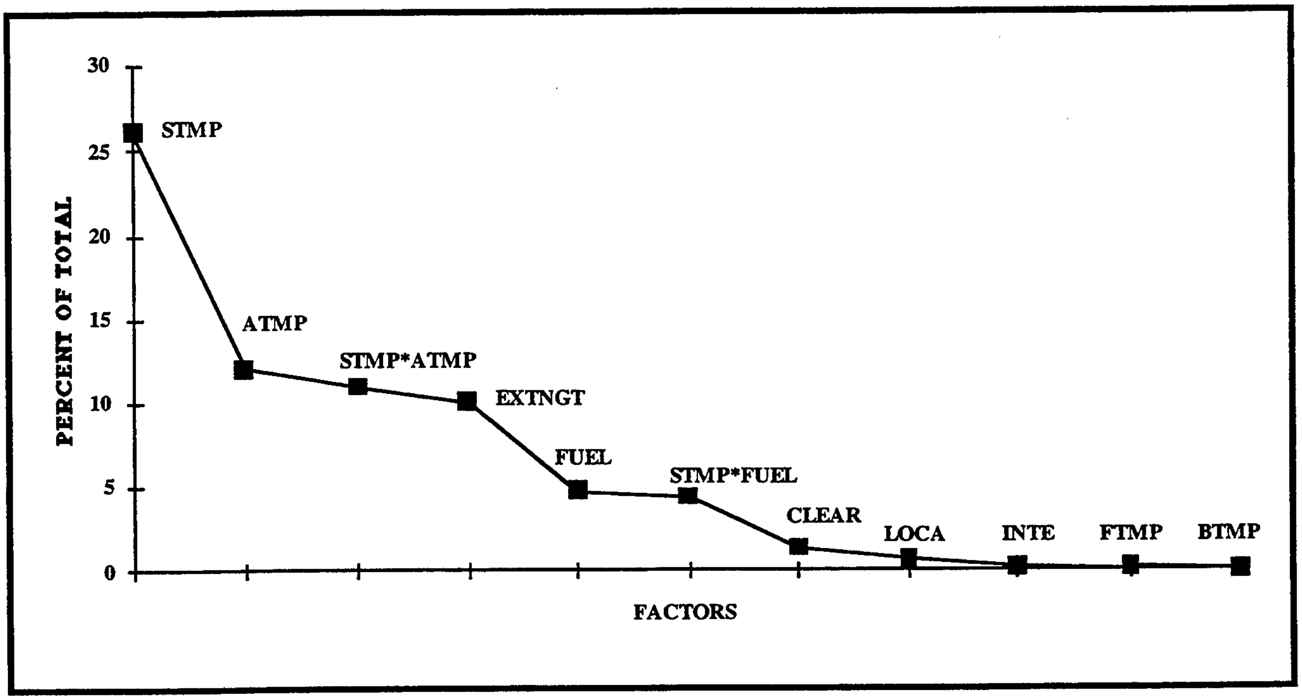

Figure 4-1. Effect Sum of Squares as Percent of Total - Phase II

Table 4-5 presents a preliminary Analysis of Variance (ANOVA) for the Phase II test matrix results. In all the ANOVA tables that follow, the following abbreviations are used:

- D.F. - degrees of freedom, which describes the relative efficiency of the different estimators. Estimates vary more with fewer degrees of freedom. As the degrees of freedom go up, the variance of a statistical distribution goes down.
- S.S. - sum of squares, calculated as the sum of the squared deviation of each observation from the mean.
- M.S. - mean square, calculated as the S.S. divided by the degrees of freedom. The greater the M.S., the greater the variance of the factor (parameter), and therefore, the more likely the factor has a statistically significant effect on the response variable (the amount of extinguishant required to extinguish a fire).
- F - F-ratio, calculated as the mean square for each factor (parameter) divided by the M.S. of the error term. When the F-ratio is close to 1.0, the estimates of the M.S. for a specific factor and the M.S. of the error are similar. This is an indication that the factor under consideration probably does not have a significant effect on the response variable. However, when the F-ratio is large, the estimates are dissimilar, and this dissimilarity is taken to be an indication of potential real effect of the factor on the response variable. The F-ratio can also be thought of as discriminating between the real effects (signal) of each factor and statistical fluctuations (noise).

Table 4-5. Preliminary Analysis of Variance (ANOVA) - Phase II

PARAMETER	D.F.	S.S.	M.S.	F
STMP	1	579.957	579.957	33.189
ATMP	1	270.622	270.622	15.487
STMP*ATMP	1	249.418	249.418	14.273
EXTNGT	2	225.767	112.884	6.460
FUEL	1	107.751	107.751	6.166
STMP*FUEL	1	96.257	96.257	5.509
ERROR	40	698.970	17.474	
TOTAL	47	2228.740		

These effects are statistically significant at the 0.05 level of confidence; that is, there is a 95% level of confidence that these variables are significant effects on the amount of extinguishant required to extinguish an engine nacelle fire. Those effects that are not significant at this level are "pooled" into the experimental error term.

4.1.2 Transformation of the Response Variable

When performing an analysis of data, it is often the case that the data are better analyzed using a transformation of the response variable rather than the original units in which the data are reported. Common statistical practice dictates that an analysis of the data using a logarithm of the response variable should be considered when the range of the data is large, typically an order of magnitude or more.

To determine if a transformation of the data was needed, a plot of the residual values (the arithmetical difference between the actual and predicted values) versus predicted values was constructed. If the plot shows a purely random pattern about zero, a transformation is not indicated. Predicted values of the response variable were generated using a predictive model of the general form $\mathbf{Y = b_0 + b_1*X_1 + b_2*X_2 +...+ b_k*X_k}$. Such a model can be fitted to the experimental conditions and used to generate predicted values. Here the X_i's are the factors (parameters), in their standard units and test values, that are judged to stand out from the "noise". The remaining factors are set equal to zero. Based on the Phase II engine nacelle test matrix, the following predictive equations were developed.

HFC-227ea: **Predicted Amount of Extinguishant = 1.201317 + 0.358399*FUEL + 0.00702*ATMP + 0.014863*STMP - 0.000046*STMP*ATMP - 0.002518*STMP*FUEL**

HFC-125: **Predicted Amount of Extinguishant = 0.283192 + 0.358399*FUEL + 0.00702*ATMP + 0.014863*STMP - 0.000046*STMP*ATMP - 0.002518*STMP*FUEL**

CF_3I: **Predicted Amount of Extinguishant = -3.789121 + 0.358399*FUEL + 0.00702*ATMP + 0.014863*STMP - 0.000046*STMP*ATMP - 0.002518*STMP*FUEL**

Please note that the b_0 and b_i values are based on model development with the factors (X_i's) in their standard units and test values, except for the factor Fuel which used the coded values (-1/+1, corresponding to the tested extreme low and high values of each factor) for MIL-H-83282 hydraulic fluid and JP-8, respectively. Different values for b_0 and the b_i's would have

been derived if coded values had been used for all the factors. Using this model to generate predicted values, a plot of residuals versus predicted values was constructed and is shown in Figure 4-2. This plot does not show the characteristics of a "random" scatter about zero that would be expected if the underlying assumptions of the analysis were satisfied. Rather, the plot indicates that an analysis should be considered using some transformation of the original response variable. Accordingly, a log transformation was performed and the data reanalyzed. Negative predicted values are the result of inaccuracies associated with the predictions of the models.

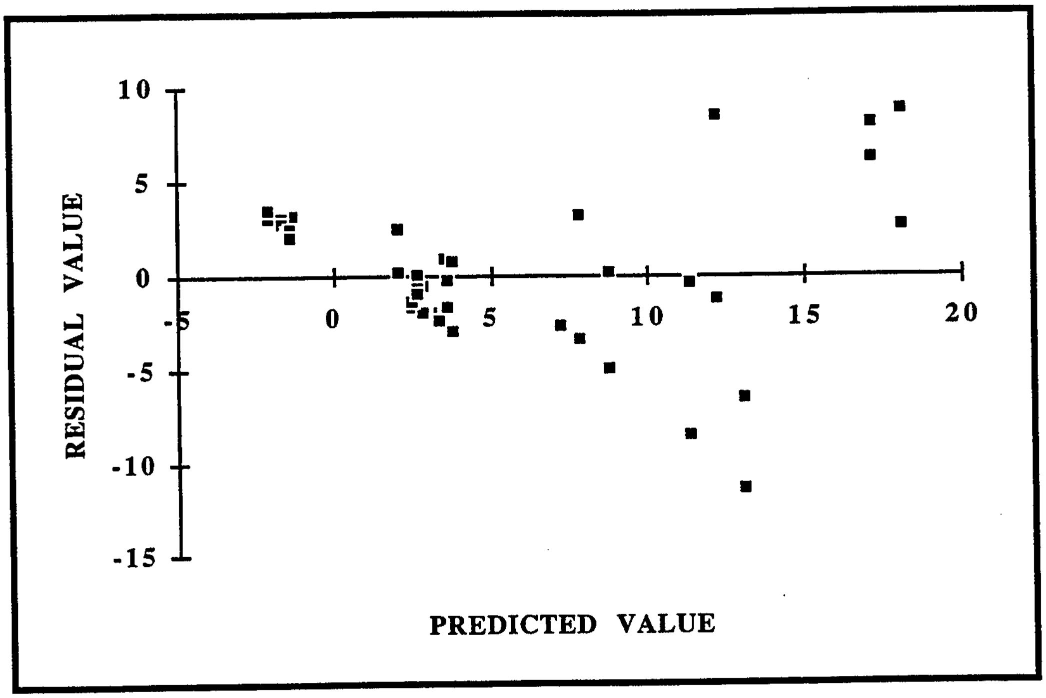

Figure 4-2. Residual Values Versus Predicted Values
(Plot not in time order)

4.1.3 Analysis of the Phase II Factorial Experiment After Log Transformation

Table 4-6 shows the results of analysis of the factorial experimental data after performing a logarithmic transformation.

Table 4-6. Analysis of the Phase II Factorial Experiment After Log Transformation

PARAMETER	SUM OF SQUARES	PERCENT OF TOTAL
STMP	20.685	39.000
EXTNGT	8.084	15.242
ATMP	5.245	9.889
STMP*ATMP	3.060	5.769
LOCA	2.053	3.871
FUEL	1.504	2.836
STMP*FUEL	1.018	1.919
CLEAR	0.079	0.149
FTMP	0.017	0.032
BTMP	0.009	0.017
INTE	0.004	0.008
TOTAL	53.039*	

*The total sum of squares is larger than the value obtained by adding the effects sum of squares in the table since the total includes the sum of squares for error (See Table 4-7). This is the usual total sum of squares outputted by most statistical software packages.

Analysis of the transformed data shows that the factors that most influence the amount of extinguishant required to extinguish the fires, based on the percentage of total variability explained, are:

- STMP - 39%
- EXTNGT -15%
- ATMP -10%
- LOCA - 4%

The factor Extinguishant Bottle Temperature (BTMP) was again shown to not be significant in the engine nacelle fire extinguishment phenomenon. The remaining factors are 3% or less of the total variability explained.

Two two-factor interactions are shown in Table 4-6. The STMP*ATMP interaction has a significant percentage of total variability explained - 6% - while the STMP*FUEL interaction is reduced to 2% of the total variability explained. With the log transformation, the significance of the two-factor interactions has been lessened.

The scree plot for the transformed data is shown below in Figure 4-3.

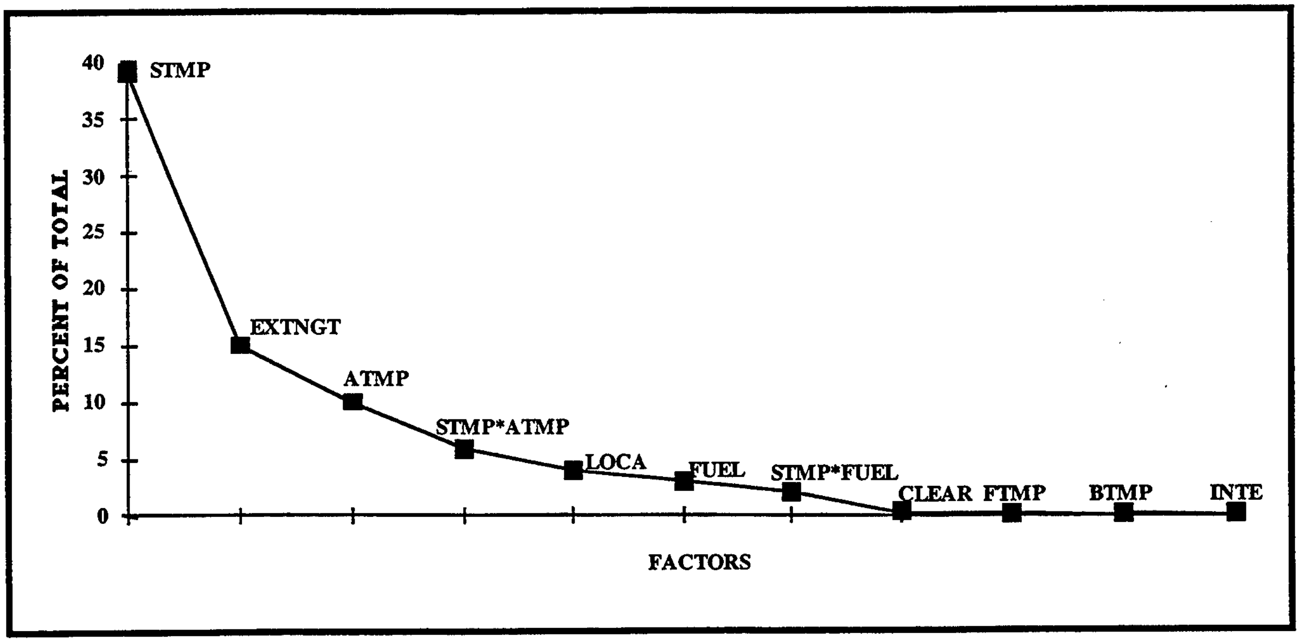

Figure 4-3. Effect Sum of Squares as Percent of Total After Log Transformation

Table 4-7. ANOVA After Log Transformation - Phase II

PARAMETER	D.F.	S.S.	M.S.	F
STMP	1	20.685	20.685	66.726
EXTNGT	2	8.084	4.042	13.039
ATMP	1	5.245	5.245	16.919
STMP*ATMP	1	3.060	3.060	9.871
LOCA	1	2.053	2.053	6.623
FUEL	1	1.504	1.504	4.852
ERROR	40	12.408	0.310	
TOTAL	47	53.039		

These effects are statistically significant at the 0.05 level of confidence; that is, there is a 95% level of confidence that these variables are significant effects on the amount of extinguishant required to extinguish an engine nacelle fire. Those effects that are not significant at this level are "pooled" into the experimental error term.

Predictive models were again developed as described previously in paragraph 4.1.2 and used to generate predicted values.

HFC-227ea: **Ln(Predicted Amount of Extinguishant) = 0.491789 + 0.002129*STMP + 0.000005*ATMP - 0.206828*LOCA - 0.176997*FUEL - 0.000005*STMP*ATMP**

HFC-125: **Ln(Predicted Amount of Extinguishant) = 0.366227 + 0.002129*STMP + 0.000005*ATMP - 0.206828*LOCA - 0.176997*FUEL - 0.000005*STMP*ATMP**

CF_3I: **Ln(Predicted Amount of Extinguishant) = -0.434731 + 0.002129*STMP + 0.000005*ATMP - 0.206828*LOCA - 0.176997*FUEL - 0.000005*STMP*ATMP**

A plot of residual values verses predicted values (Figure 4-4) was again constructed. The residual plot now looks much more like a random scatter plot of points about zero. Negative predicted values are the result of the logarithmic transformation of a number less than 1 or inaccuracies associated with the predictions of the models.

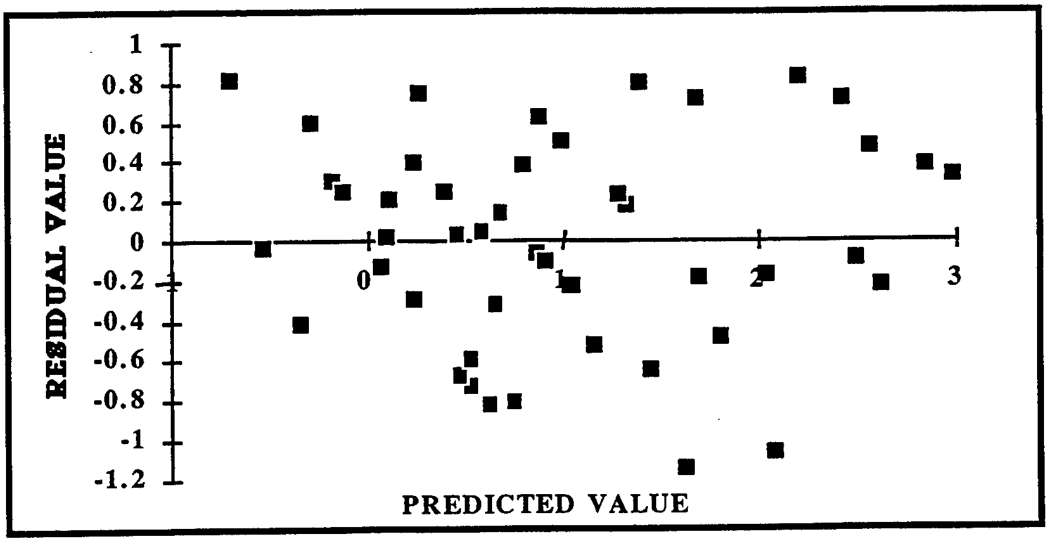

Figure 4-4. Residual Values Versus Predicted Values After Log Transformation
(Plot not in time order)

4.2 Phase II Analysis Summary

Data analyses were performed on the original response variable (weight of extinguishant required to extinguish fire) and on the logarithm of the response variable. The conclusions were similar for both analyses. The most important factors and interactions influencing the response were:

- Surface Temperature (STMP)
- Air Temperature (ATMP)
- Extinguishant (EXTNGT)
- Fuel Type (FUEL)
- Surface Temperature*Air Temperature (STMP*ATMP) interation

In addition, analysis of the transformed data indicated that Fire Location (LOCA) was a significant parameter. Analysis of the original data showed that the Surface Temperature*Fuel Type (STMP*FUEL) interaction was also a significant parameter.

The residual plot, after making the log transformation, gave a strong indication that the residual terms were randomly distributed and were independent of the mean response.

Analysis of the original data also showed that the candidate extinguishant CF_3I was clearly superior to the other extinguishants, and that this result was statistically significant at the 0.05 level. That is, there is 95% confidence that CF_3I was indeed clearly superior to the other extinguishants. Table 4-8 shows the average weight of the extinguishants required.

Table 4-8. Average Weight of Extinguishants (lbs) - Phase II

EXTINGUISHANT	16 TESTS
HFC-227ea	7.075
HFC-125	6.157
CF_3I	2.085

5.0 CONCLUSIONS

The objective of this phase of the testing for the Halon Replacement Program for Aviation was to develop full-scale live fire test data comparing the three selected candidate replacement extinguishants. The data that were generated under this test program were presented at a Technology Transition (T2) team meeting in October 1994 at NIST. At this meeting, the T2 team members were to review all the data related to the candidate extinguishants, including the data generated under the test program documented in this report, and select the best halon replacement for further evaluation from among the three tested. Additional data considered during the selection process included information on toxicity, costs, and corrosivity.

Based solely on the data presented in this report, the extinguishant CF_3I was shown to be clearly superior in fire extinguishing performance, pound for pound, to the other extinguishants tested. Under various test conditions, it was shown to require on average significantly less extinguishant to extinguish the engine nacelle fires and is comparable to Halon 1301 in performance. Based on an average of the 16 test configurations evaluated for each extinguishant, the amount of CF_3I required was only 34% of the amount of the next best extinguishant - HFC-125.

Although CF_3I was superior in extinguishing performance among the tested extinguishants, HFC-125 was selected by the T2 team as the extinguishant to take forward into Phase III. This decision was due to questions of cardiotoxicity raised about CF_3I based on recent data and due to the superior cold temperature distribution capability and "Halon 1301-like" flow and discharge behavior of HFC-125, as well as a slight observed performance advantage over HFC-227ea.

6.0 REFERENCES

1. Little, Bennett, Lee, "Comprehensive Test Plan, Halon Replacement Program for Aviation", October 1992.

2. Ball, Robert E., "The Fundamentals of Aircraft Combat Survivability Analysis and Design", 1985.

3. Bennett, Caggianelli, Kolleck, Wheeler, "Halon Replacement Program for Aviation, Aircraft Engine Nacelle Application - Phase I - Operational Parameters Study", WL-TR-95-3077, April 1997.

4. National Institute of Standards and Technology NIST SP 861, "Evaluation of Alternative In-Flight Fire Suppressants for Full Scale Testing in Simulated Aircraft Engine Nacelles and Dry Bays", April 1994.